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D5.9 - Definition of the benchmark parameters and loop geometry

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sCO2-Flex

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Technical References

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[1] PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

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3.2			

Summary

This deliverable provides definition of the boundary conditions for benchmarking of computational codes (Modelica based libraries) with experimental data from a supercritical CO2 (sCO2) loop at CV Rez.

The sCO2 experimental facility, primarily used for simulating the system behavior of sCO2 Brayton cycles, is described (loop geometry, nominal pressures, temperatures, heating power and mass flow rate, etc.) to allow preparation of the computational models. In addition to that, several steady states experimental data (nominal, off-design) are given in order to tune the numerical models, and the detail input description of the selected steady states and transients is outlined.
The benchmark itself, together with evaluation of suitability of the codes for simulating sCO2 power plants and enhancement of their abilities, will be described in the upcoming deliverable D.5.10 Final report on the computational codes benchmarking.

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Introduction

Within the framework of its participation in the sCO2-Flex project, CV Rez has offered the experimental tests in the supercritical CO2 (sCO2) facility, located in the research center of CV Rez (Research Centre Rez) in the Czech Republic [1], for the organization of a benchmark exercise aimed at the validation of the thermal hydraulic system codes for sCO2 power plants.

Although the loop characteristics are not prototypical of the foreseen sCO2 power plant, e.g. compressor is substituted by a piston pump and turbine by a reduction valve, the tests were judged useful to assess the capability of the codes to deal with the thermal-hydraulic behavior of the sCO2 loop implementing a wide range of components such as compressor (pump), pressurizer, pipes, diffusers, reduction (expansion) valve, heaters, heat exchangers and test section.

The test campaign which has been performed during the third quarter of 2018 includes both steady-state and transient conditions. Steady-states at different temperatures, pressures and mass–flow rates have been considered to test the models in a wide operating range, and several transients such as loss of heat sink, sudden change of mass flow rate or heating power have been considered to assess the models in dynamic conditions.

This deliverable provides definition of the boundary conditions for benchmarking of computational codes (Modelica based libraries) with the experimental data. The sCO2 experimental facility, used for simulating the system behavior of sCO2 Brayton cycle, is described (loop geometry, nominal pressures, temperatures, heating power and mass flow rate, etc.). In addition to that, several steady states experimental data (nominal, off-design) are given in order to tune the numerical models and the detail input description of the selected transients. The benchmark itself, together with evaluation of suitability of the codes for simulating sCO2 power plants and enhancement of their abilities, will be described in the upcoming deliverable D.5.10 Final report on the computational codes benchmarking.

The benchmark calculations will be performed independently by the participating teams (CV Rez and POLIMI) using different thermal hydraulic Modelica based libraries such as ThermoPower and ClaRa. Several environments for the Modelica language exist. For current analysis, the Dymola [2] has been chosen for its compatibility with the Modelica libraries.

The objective of the exercise is to verify that the outlined system codes used for the transient analysis are able to correctly reproduce the sCO2 system thermal hydraulic behavior both in steady-state and transient conditions. The outcomes could be useful to provide recommendations on a sCO2 power plant modeling and for the development of consistent numerical models. Moreover, highlighting the weakness in some aspects of the present approach, it is possible to suggest the needs of codes development.

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1. Description of the loop and geometry specifications

The sCO2 experimental loop at CV Rez was constructed within SUSEN (Sustainable Energy) project in 2017. This unique facility enables component testing of sCO2 Brayton cycle such as compressor, turbine, HX, valves and to study key aspects of the cycle (heat transfer, erosion, corrosion etc.) with wide range of parameters: temperature up to 550°C, pressure up to 30 MPa and mass flow rate up to 0.35 kg/s. The loop is designed to represent sCO_2 Brayton cycle behavior.

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Annex 1 shows the piping and instrumentation diagram (PID) of the loop. The primary circuit is marked in thick red and it consists of following main components:

- The piston-type main pump (MP), which circulates sCO_2 through the circuit with the variable speed drive for the flow rate control.
- The high and low temperature regenerative heat exchangers (HTR HX/LTR HX), which recuperate the heat, hence reduce the heating and cooling power.
- The 4 electric heaters (H1/1, H1/2, H2, H3), which have in total a maximum power of 110 kW and raise the temperature of sCO_2 to the desired test section (TS) inlet temperature up to 550°C.
- The reduction valve which consists of series of orifices to reduce the pressure and together with oil (Marlotherm SH) cooler (CH2) represent a turbine.
- The water cooler (CH1) cools down the sCO_2 at the inlet of the MP by water cooling circuit. The secondary water cooling circuit is cooled by tertiary water cooling circuit. PID of the sCO2 loop does not depict tertiary water cooling circuit for simplification matter of the benchmark exercise. The complete set of boundary conditions are defined for the secondary water cooling circuit allowing this reduced approach.
- Air driven filling (reciprocating) compressor (gas booster station) which pumps the sCO_2 from the CO_2 bottles and also controls the operating pressure.
- Exhaust system for the excess amount of sCO2

The PID of the sCO2 loop contains all installed key measurement devices, such as a mass flow meter, Pt-100 sensors, thermocouples, pressure sensors and wattmeters. The nomenclature of the measurement devices respects the KKS identification system for power plants.

The uncertainties provided by the measurement devices, transducer, input card, and control system are summarized in Annex 2. The errors correspond to calibration certificates and manufacturer's instructions.

The zig-zag line at the PID stands for the oil cooler CH2 and connected pipeline. This line was closed during testing campaign since it was not needed to have extra cooling power in oil cooling circuit.

The main operating parameters of the primary circuit are shown in Table 1.

Table 1: The main operating parameters of the sCO2 primary loop.

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

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The sCO_2 loop layout is depicted in Figure 1 and the top view of the built facility is shown in Figure 2.

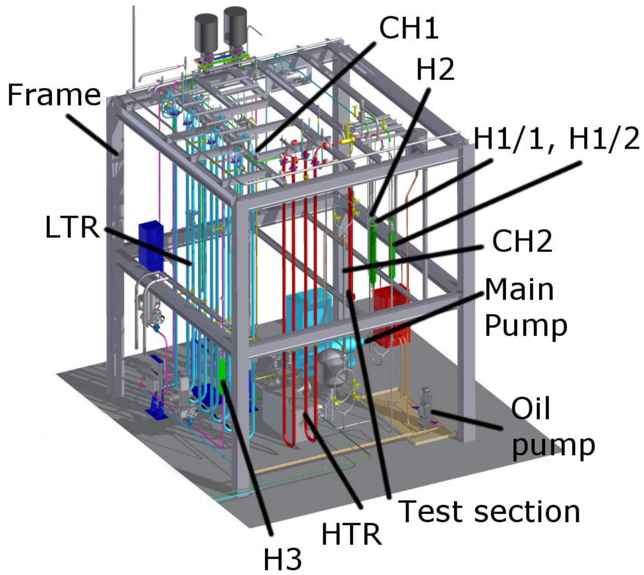

Figure 1: 3D CAD model of the sCO_2 loop.

Figure 2: A view from the top on the built sCO_2 loop.

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Table 2 summarizes parameters of the MP and the schematic cross-section of the MP is shown in Figure 3.

Table 2: Parameters of the main pump.

Device	Main Pump - PAX-3-30-18-250-YC-CRYO-drive 9/FM
Nominal inlet pressure	12.5 MPa
Nominal outlet pressure	25 MPa
Maximal outlet pressure	30 MPa
Nominal inlet temperature	25°C
Maximum inlet temperature	50°C
Nominal isentropic efficiency	0.7
Rotational speed (manufacturer data)	250÷1460 rpm
Volumetric flowrate (manufacturer data)	5÷30 l/min.
Rotational speed -> Volumetric flowrate (measurement data)	555 rpm -> 9.8 l/min 935 rpm -> 16.7 l/min

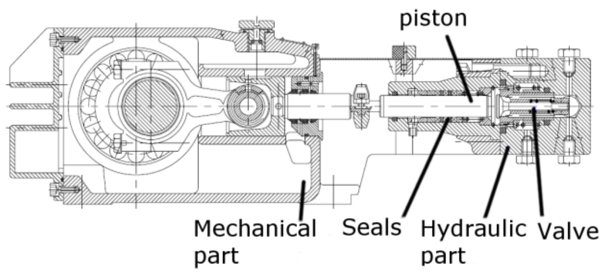

Figure 3: Cross-section of main pump.

In Table 3, the main parameters of the filling compressor are listed.

Table 3: Parameters of the filling compressor.

Device	Filling compressor - DLE5-15-GG-C
Nominal inlet pressure of CO_2	0.5 MPa
Nominal outlet pressure	6.5 MPa
Maximum outlet pressure	30 MPa
Nominal flowrate	15 standard litre per minute

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Nominal air pressure	0.6 MPa

Geometric parameters of the heat exchanging components of the sCO_2 loop needed for preparation of the model are described in Table 4. The parameters needed for the model settings such as pipe diameters and lengths, layouts of heat exchangers and heaters and materials are listed for each component according to PID scheme in the annex.

Table 4: Component geometry of the sCO_2 loop

Component	Geometry
HTR + LTR (counter-flow shell and tube-type from SS 321)	Length of HTR = 20 m (2 x U-tube vertical), 3 x 2 = 6 high pressure flanges Ø 110 mm (height 25 mm) and the same 6 low pressure flanges Length of LTR = 60 m (6 x U-tube vertical), 7 x 2 = 14 high pressure flanges Ø 110 mm (height 25 mm) and the same 14 low pressure flanges Number of internal tubes = 7, Internal tube Ø 10 x 1.5 mm, Shell Ø 50 x 5 mm.
H1/1 + H1/2 (30 + 30 kW) (from SS 321)	Length = 0.95 m, Number of heating rods = 2 x 6, Diameter of a heating rod Ø 8 mm (cladding tube Ø 8 x 1 mm SS 321, ceramic (MgO) filling Ø 6 x 1 mm, ceramic (Al2O3) filling Ø 4 x 1.75 mm, Ø 0.5 mm wire Kanthal alloy (FeCrAl)), Shell Ø 100 x 20 mm, guiding tube Ø 36 x 2 mm with plugs on both ends
H2 (30 kW) (from Inconel 625)	Length = 0.95 m, Number of heating rods = 2 x 6, Diameter of a heating rod 8 mm (ceramic filling and wire as in H1/1 + H1/2), Shell Ø 73 x 6.5 mm, 2 x 1 = 2 flanges Ø 110 mm (height 25 mm), guiding tube Ø 36 x 2 mm with plugs on both ends
H3 (20 kW) (from SS 321)	Length = 0.75 m, Number of heating rods = 2 x 6, Diameter of a heating rod Ø 8 mm (ceramic filling and wire as in H1/1 + H1/2), Shell Ø 100 x 20 mm, guiding tube Ø 36 x 2 mm with plugs on both ends
CH1 (counter-flow shell and tube-type from SS)	Length = 7.5 m, Number of internal tubes = 7, Internal tube Ø 10 x 1.5 mm, Shell Ø 43 x 1.5 mm
CH2 (counter-flow shell and tube-type from Inconel 625 (CO2 side)/SS 321 (oil side))	Length = 1.8 m, Number of internal tubes = 7, Internal tube Ø 10 x 1.5 mm, Shell Ø 43 x 1.5 mm, 2 x 2 = 4 high flanges Ø 110 mm (height 25 mm)
TS	Length = 2 m, Shell Ø 73 x 6.5 mm, 2 x 2 = 4 high flanges Ø 140 mm (height 26 mm)

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(from Inconel 625)	
Reduction valve (from SS 321)	Body weight 125 kg, Length = 0.5 m
Control valves (3x) (from SS 321)	Body weight 5 kg, Length = 0.3 m (each)
Closing valves *("hot" part of the loop) (from SS 321)	Body weight 1 kg, Length = 0.3 m (each)
Closing valves **("cold" part of the loop) (from SS 321)	Body weight 5 kg, Length = 0.3 m (each)

** The "hot" part of the loop is from inlet of heater H3 and inlet of high pressure LTR to outlet of low pressure LTR.*

*** The "cold" part is the rest of the loop (from outlet of low pressure LTR to inlet to heater H3 and inlet of high pressure LTR.*

The geometry of HTR heat exchangers is demonstrated in Figure 4. It is a counter-current shell and tube heat exchanger and it concludes of 2 U-tube modules. The LTR heat exchanger is of a same type and it includes 6 U-tube modules.

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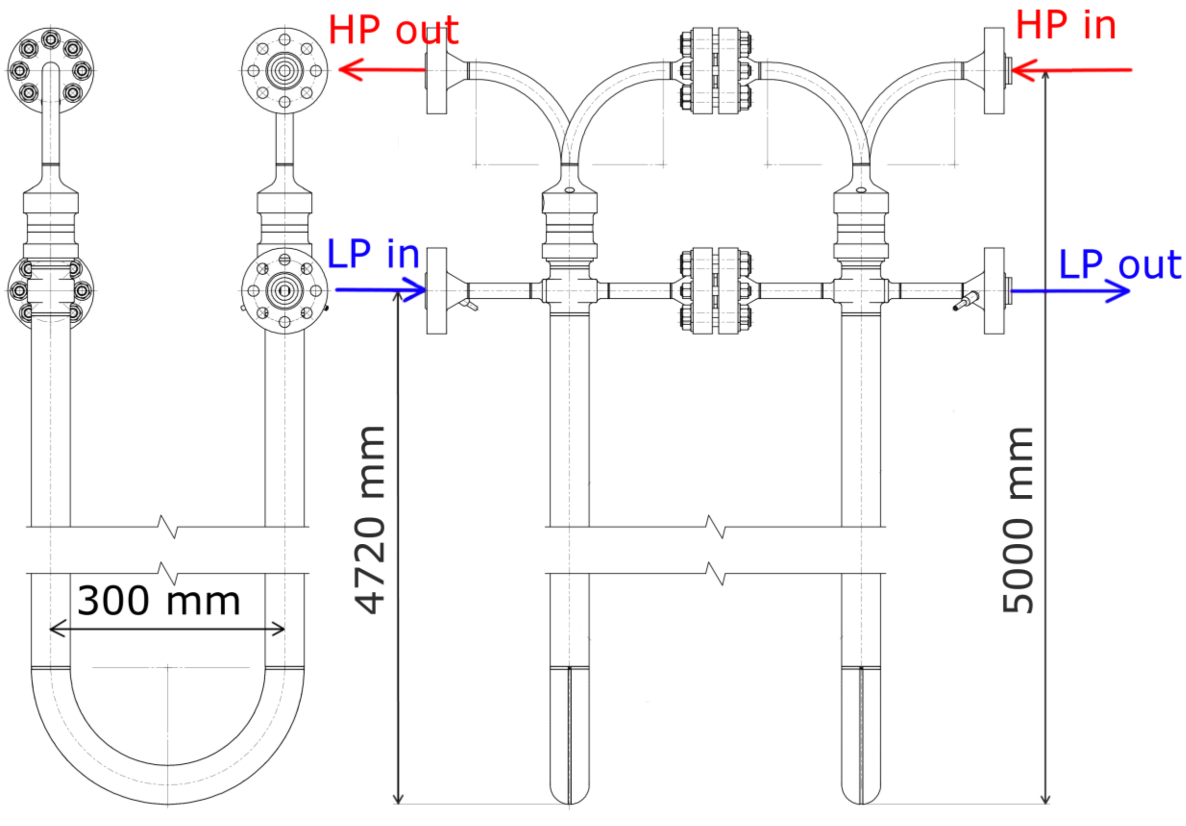

Figure 4: HTR heat exchanger.

The geometry of the tube plate LTR/HTR heat exchanger of inserted in a shell is displayed in Figure 5.

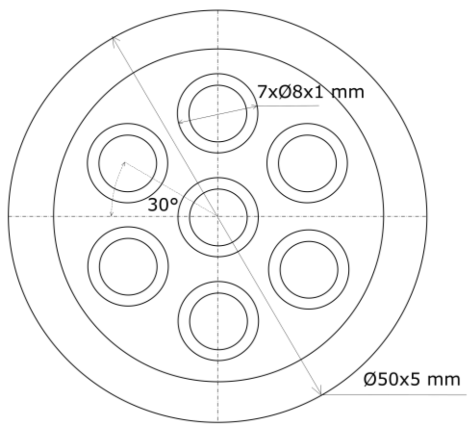

Figure 5: LTR/HTR heat exchanger tube plate in a shell.

The cross cut of electrical heater rod of H1/1, H1/2, H2 and H3 is shown in Figure 6.

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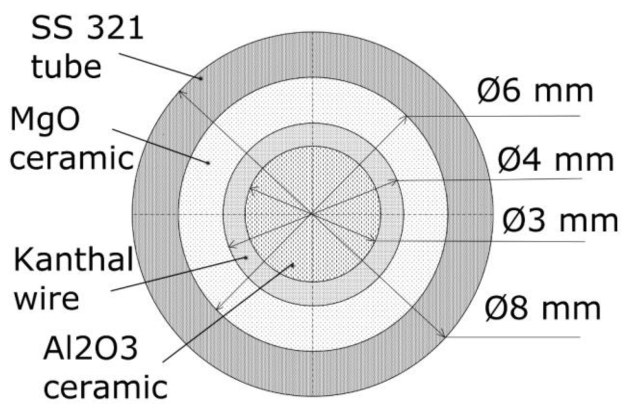

Figure 6: Electrical heater rod cross cut.

The cross cut of electrical heaters of H1/1, H1/2 H3 are shown in Figure 7 and H2 in Figure 8. All heaters are equipped with guiding tube Ø 36 x 2 mm which directs the flow around the electrical heater rods. This tube is plugged on both ends.

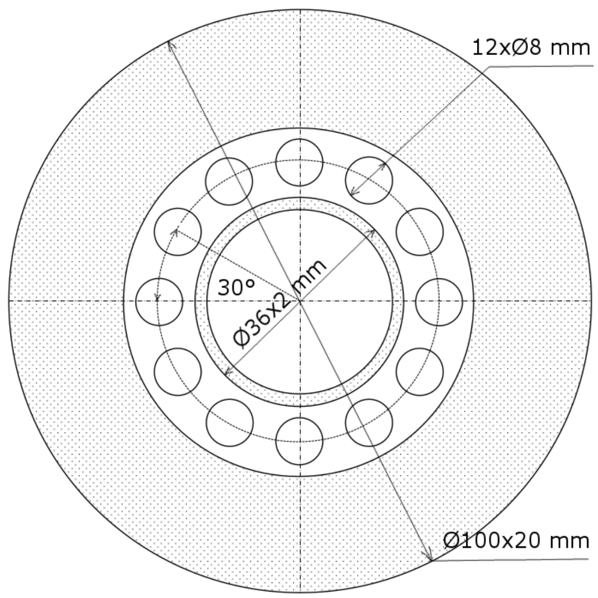

Figure 7: Electrical heater H1/1, H1/2 and H3 cross cut.

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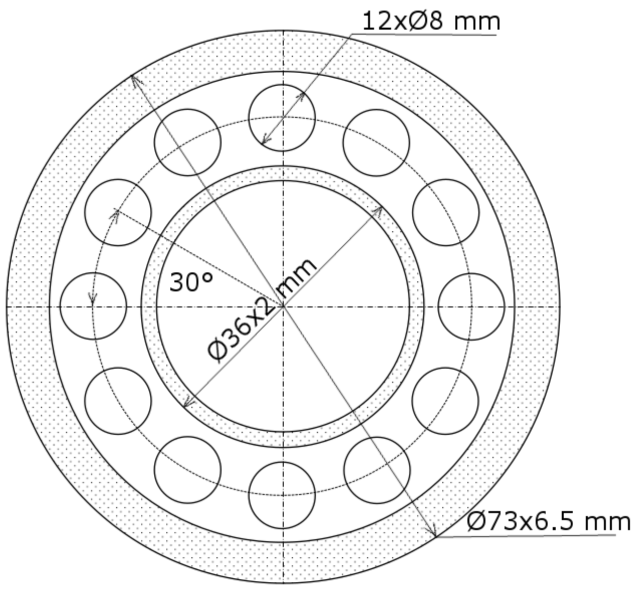

Figure 8: Electrical heater H2 cross cut.

The electrical heater H3 with nominal power 20 kW is positioned at the bypass of the LTR in order to simulate the behavior of a recompression cycle.

The pressure loss coefficients of the valves related to cross-section areas of corresponding pipelines (inner diameter 14 mm) are listed in Table 5.

Table 5: Pressure loss coefficient of the fully-open valves

Valve type	Pressure loss coefficient [-]
Reduction valve (characteristic in Table 6)	827
Control valves (linear characteristic)	14
Closing valves ("hot" part of the loop)	12
Closing valves ("cold" part of the loop)	4

The reduction valve characteristic Opening versus Kv/Kvs of the reduction valve is displayed in Table 6. Averaged values of Kv/Kvs from all measured data covering temperature range 50°C ÷ 450°C are given (no data from manufacturer are available).

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Table 6: Characteristic of the of the reduction valve.

Opening [%]	Kv/Kvs [-]
0	0.09
40.5	0.45
45	0.52
50	0.59
55	0.65
60	0.70
65	0.74
70	0.79
75	0.85
80	0.90
85	0.92
90	0.95
95	0.97
100	1.00

The geometric parameters of pipelines according to the PID scheme are summarized in Table 7 including the pipe diameters and lengths. Parameters of bends are also mentioned to allow modelling of local pressure losses.

Table 7: Pipeline geometry of the sCO_2 loop

Line 1	Pipeline from MP to T-junction LTR by-pass	Length = 2.6 m, 1x90° Bend, Tube Ø 22 x 4 mm
Line 2	Pipeline from T-junction LTR by-pass to LTR	Length = 6.8 m, 6x90° Bend, Tube Ø 22 x 4 mm
Line 3	LTR by-pass	Length = 7.6 m, 2x90° Bend, Tube Ø 22 x 4 mm
Line 4	Pipeline from outlet of high pressure LTR to inlet of high pressure HTR	Length = 0.7 m, 2x90° Bend, Tube Ø 22 x 4 mm

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Line 5	Pipeline from outlet of high pressure HTR to T-junction at the inlet of H1/1 and H1/2	Length = 1 m, 1x90° Bend, Tube Ø 22 x 4 mm
Line 6a/6b	2 identical pipelines from T-junction at the inlet of H1/1 and H1/2 to H1/1 and H1/2	Length = 1.4 m, 1x60° Bend, Tube Ø 22 x 4 mm
Line 7a/7b	2 identical pipelines from H1/1 and H1/2 to T-junction at the outlet of H1/1 and H1/2	Length = 1.5 m, 1x60° Bend, Tube Ø 22 x 4 mm
Line 8	Pipeline from T-junction outlet of H1/1 and H1/2 to H2	Length = 1.9 m, 2x90° Bend, Tube Ø 22 x 4 mm
Line 9	Pipeline from H2 to test section	Length = 2 m, 2x90° Bend, Tube Ø 22 x 4 mm
Line 10	Pipeline from test section to reduction valve	Length = 1.9 m, 1x90° Bend, Tube Ø 22 x 4 mm
Line 11	Pipeline from reduction valve to T-junction of line 12a/13	Length = 8.4 m, 8x90° Bend, Tube Ø 20 x 3 mm
Line 12a	Pipeline from T-junction of line 12a/13 to T-junction CH2 by-pass (inlet of CH2 by-pass)	Length = 0.4 m, 1x60° Bend, Tube Ø 20 x 3 mm
Line 12b	Pipeline from T-junction CH2 by-pass (inlet of CH2 by-pass) to T-junction of line 12b/13	Length = 0.4 m, 1x60° Bend, Tube Ø 20 x 3 mm
Line 13	Pipeline from T-junction of line 12a/13 to T-junction of line 12b/13 to	Length = 0.9 m, 2x60° Bend, Tube Ø 20 x 3 mm
Line 14	Pipeline CH2 by-pass	Length = 5.5 m, 4x90° Bend, Tube Ø 20 x 3 mm
Line 15a	Pipeline from T-junction of line 15a/16 to T-junction CH2 by-pass (outlet of CH2 by-pass)	Length = 0.4 m, 1x60° Bend, Tube Ø 20 x 3 mm
Line 15b	Pipeline from T-junction CH2 by-pass (outlet of CH2 by-pass) to T-junction of line 15b/16	Length = 0.4 m, 1x60° Bend, Tube Ø 20 x 3 mm
Line 16	Pipeline from T-junction of line 15a/16 to T-junction of line 15b/16	Length = 0.9 m, 2x60° Bend, Tube Ø 20 x 3 mm
Line 17	Pipeline from T-junction of line 15b/16 to inlet of low pressure HTR	Length = 0.8 m, 1x90° Bend, Tube Ø 20 x 3 mm
Line 18	Pipeline from outlet of low pressure HTR to inlet of low pressure LTR	Length = 0.7 m, 2x90° Bend, Tube Ø 22 x 4 mm
Line 19	Pipeline from outlet of low pressure LTR to CH1	Length = 1.8 m, 2x90° Bend, Tube Ø 20 x 3 mm

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Line 20	Pipeline from CH1 to MP	Length = 4.4 m, 7x90° Bend, Tube Ø 20 x 3 mm

The "hot" parts (from inlet to heater H3 and inlet of high pressure LTR to outlet of low pressure LTR) of the loop are insulated with rock wool Orstech DP 100. The test section and heaters are insulated with 0.14 m thickness and the rest with 0.1 m. Thermal conductivity of the insulation material depending on temperature is shown in Table 8. The insulation on the RV (of length of approximately 0.5 m) is not installed.

Table 8: Thermal conductivity of the insulation

T [°C]	50	100	150	200	250	300	400	500	600	680
λ [W/mK]	0.041	0.047	0.054	0.063	0.073	0.084	0.110	0.143	0.182	0.219

In Table 9, locations of measurement sensors corresponding to the loop layout are listed. The positions of the sensors have to be taken into account in the computational models as well. The table includes all needed sensors of temperature, pressure, mass-flow rate, heating powers and pump speed. Apart from this, positions of valves are also mentioned. Layout of the sensors can be also seen in the PID diagram.

Table 9: Position of the measurement sensors

Measurement type	Position	Pipeline
m_CO2_MP (1LKB70CF001)	3.9 m prior to MP inlet	line 20
m_CO2_LTR (1LKB10CF001)	1.6 m from MP outlet	line 1
rotational speed_MP (1LKC10CS001)	MP	line 1
power_H1/1 (1LKD40CE011A)	H1/1	line 6b,7b
power_H1/2 (1LKD40CE011B)	H1/2	line 6a,7a
power_H2 (1LKD40CE011C)	H2	line 8,9
power_H3 (1LKD10CE011)	H3	line 3
p_CO2_MP_in (1LKB70CP001)	3.4 m prior to MP inlet	line 20
T_CO2_MP_in (1LKB70CT001)	5.1 m prior to MP inlet	line 20
p_CO2_MP_out (1LKB10CP001)	1.6 m prior to MP outlet	line 1
T_CO2_MP_out (1LKB10CT001)	1.6 m prior to MP outlet	line 1
position_valve_LTR_in (1LKB10CG001)	control valve LTR inlet	line 2

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position_valve_LTR_by-pass (1LKB11CG001)	control valve LTR by-pass	line 3
T_by-pass LTR (1LKB12CT001)	0.8 m prior to H3 outlet	line 3
p_CO2_LTR_p_high_side_in (1LKB10CP003)	LTR high pressure inlet	line 2
T_CO2_LTR_p_high_side_in (1LKB10CT002)	LTR high pressure inlet	line 2
p_CO2_LTR_p_high_side_out (1LKB20CP001)	HTR high pressure inlet	line 4
T_CO2_LTR_p_high_side_out (1LKB20CT001)	HTR high pressure inlet	line 4
T_CO2_HTR_p_high_side_out (1LKB30CT001)	HTR high pressure outlet	line 5
p_CO2_HTR_p_high_side_out (1LKB30CP001)	HTR high pressure outlet	line 5
T_CO2_H1/1_H1/2_in (1LKD40CT001)	H1/1, H1/2 inlet (T-junction)	line 5
T_CO2_H1/1_out (1LKD40CT002)	H1/1, H1/2 outlet (T-junction)	line 7b
T_CO2_H1/2_out (1LKD40CT003)	H1/1, H1/2 outlet (T-junction)	line 7a
T_CO2_H2_out (1LKD40CT004)	1.2 m prior to H2 outlet	line 9
p_CO2_RV_in (1LKB31CP001)	TS outlet	line 10
T_CO2_RV_in (1LKB31CT001)	TS outlet	line 10
position of RV (1LKB31CG001)	RV	line 11
position_valve_CH2_by-pass (1LKB40CG001)	control valve CH2 by-pass	line 14
p_CO2_HTR_p_low_side_in (1LKB42CP001)	HTR low pressure inlet	line 17
T_CO2_HTR_p_low_side_in (1LKB42CT001)	HTR low pressure inlet	line 17
p_CO2_HTR_p_low_side_out (1LKB50CP001)	HTR low pressure outlet	line 18
T_CO2_HTR_p_low_side_out (1LKB50CT001)	HTR low pressure outlet	line 18
p_CO2_LTR_p_low_side_out (1LKB60CP001)	LTR low pressure outlet	line 19
T_CO2_LTR_p_low_side_out (1LKB60CT001)	LTR low pressure outlet	line 19
m_H2O_CH1 (1PGG20CF001)	1.4 m prior to CH1 inlet	water circuit
T_H2O_CH1_in (1PGG20CT001)	CH1 inlet	water

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		circuit
T_H2O_CH1_out (1PGG30CT001)	CH1 outlet	water circuit

2. Steady-states

As a part of the CV Rez sCO2 loop experimental program for benchmark on thermal hydraulic codes, several steady states and transients data were achieved. In order to tune the numerical models, 3 steady states (covering different temperature levels and pressures) with set of relevant parameters are given in

Table **10**.

Table 10: Steady state parameters

Measurement type / Measurement #	Unit	5	37	61
m_CO2_MP (1LKB70CF001)	kg/s	0.227	0.192	0.197
m_CO2_LTR (1LKB10CF001)	kg/s	0.227	0.192	0.197
rotational speed_MP (1LKC10CS001)	%	66	67	56
power_H1/1 (1LKD40CE011A)	kW	0.9	6.6	3.1
power_H1/2 (1LKD40CE011B)	kW	1	6.9	3.2
power_H2 (1LKD40CE011C)	kW	27	17.8	28.1
power_H3 (1LKD10CE011)	kW	0	0	0
p_CO2_MP_in (1LKB70CP001)	MPa	8.8	7.5	8
T_CO2_MP_in (1LKB70CT001)	°C	21.2	19.3	16.8
p_CO2_MP_out (1LKB10CP001)	MPa	19.8	20.9	20.0
T_CO2_MP_out (1LKB10CT001)	°C	34	38.6	30.8
position_valve_LTR_in (1LKB10CG001)	%	100	100	100
position_valve_LTR_by-pass (1LKB11CG001)	%	0	0	0

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T_by-pass LTR (1LKB12CT001)	°C	-	-	-
p_CO2_LTR_p_high_side_in (1LKB10CP003)	MPa	19.8	20.7	20
T_CO2_LTR_p_high_side_in (1LKB10CT002)	°C	32.5	36.7	28.9
p_CO2_LTR_p_high_side_out (1LKB20CP001)	MPa	19.7	20.6	19.8
T_CO2_LTR_p_high_side_out (1LKB20CT001)	°C	55.6	53.4	57.6
T_CO2_HTR_p_high_side_out (1LKB30CT001)	°C	70.9	208.6	343.1
p_CO2_HTR_p_high_side_out (1LKB30CP001)	MPa	19.7	20.6	19.8
T_CO2_H1/1_H1/2_in (1LKD40CT001)	°C	71	209.3	344.5
T_CO2_H1/1_out (1LKD40CT002)	°C	75	260.1	365.1
T_CO2_H1/2_out (1LKD40CT003)	°C	75.1	260	365.1
T_CO2_H2_out (1LKD40CT004)	°C	122	327.9	470
p_CO2_RV_in (1LKB31CP001)	MPa	19.7	20.5	19.7
T_CO2_RV_in (1LKB31CT001)	°C	123.2	328.4	474
position of RV (1LKB31CG001)	%	63	57	60
position_valve_CH2_by-pass (1LKB40CG001)	%	100	100	100
p_CO2_HTR_p_low_side_in (1LKB42CP001)	MPa	9.2	7.9	8.4
T_CO2_HTR_p_low_side_in (1LKB42CT001)	°C	77.8	300.2	447.7
p_CO2_HTR_p_low_side_out (1LKB50CP001)	MPa	9.2	7.9	8.4
T_CO2_HTR_p_low_side_out (1LKB50CT001)	°C	56.9	54.9	59.5
p_CO2_LTR_p_low_side_out (1LKB60CP001)	MPa	8.9	7.5	8
T_CO2_LTR_p_low_side_out (1LKB60CT001)	°C	42.2	39.2	37.9
m_H2O_CH1 (1PGG20CF001)	kg/s	1.412	0.681	0.674
T_H2O_CH1_in (1PGG20CT001)	°C	19.6	16.7	15.3
T_H2O_CH1_out (1PGG30CT001)	°C	25.4	28.9	27.2

Following Table 11 includes 8 campaigns of steady state boundary conditions covering wide range of temperatures, pressures and mass flow rates. The measurement parameters with intentionally left blank fields are subject of the benchmark exercise and are to be filled by

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benchmark participants in the upcoming deliverable D.5.10 Final report on the computational codes benchmarking in M24.

Table 11: Steady state boundary conditions

Meas. # / Meas. type		15	20	31	73	45	78	63	93
m_CO2_MP (1LKB70CF001)	kg/s	0.146	0.146	0.197	0.141	0.146	0.146	0.146	0.146
m_CO2_LTR (1LKB10CF001)	kg/s	0.146	0.146	0.197	0.141	0.146	0.146	0.146	0.146
rotational speed_MP (1LKC10CS001)	%	40	43	56	43	39	68	38	42
power_H1/1 (1LKD40CE011A)	kW	5.4	5.2	5.5	10.4	3.9	8.8	3.8	7.5
power_H1/2 (1LKD40CE011B)	kW	5.4	5.4	5.7	10.2	4	9.2	4	7.5
power_H2 (1LKD40CE011C)	kW	11.1	12.3	16.1	4.7	14.6	9.7	15.3	11.7
power_H3 (1LKD10CE011)	kW	0	0	0	0	0	0	0	0
p_CO2_MP_in (1LKB70CP001)	MPa	8	8	8.4	7.4	9.2	6.8	9.3	7.9
T_CO2_MP_in (1LKB70CT001)	°C								
p_CO2_MP_out (1LKB10CP001)	MPa								
T_CO2_MP_out (1LKB10CT001)	°C								
position_valve _LTR_in (1LKB10CG001)	%	100	100	100	100	100	100	100	100
position_valve _LTR_by-pass (1LKB11CG001)	%	0	0	0	0	0	0	0	0
T_by-pass LTR	°C	-	-	-	-	-	-	-	-

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(1LKB12CT001)									
p_CO2_LTR _p_high_side_in (1LKB10CP003)	MPa								
T_CO2_LTR _p_high_side_in (1LKB10CT002)	°C								
p_CO2_LTR_p_hi gh_side_out (1LKB20CP001)	MPa								
T_CO2_LTR _p_high_side_out (1LKB20CT001)	°C								
T_CO2_HTR _p_high_side_out (1LKB30CT001)	°C								
p_CO2_HTR _p_high_side_out (1LKB30CP001)	MPa								
T_CO2 _H1/1_H1/2_in (1LKD40CT001)	°C								
T_CO2_H1/1_out (1LKD40CT002)	°C								
T_CO2_H1/2_out (1LKD40CT003)	°C								
T_CO2_H2_out (1LKD40CT004)	°C								
p_CO2_RV_in (1LKB31CP001)	MPa	19.7	19.8	19.7	19.9	20.1	19.5	19.6	19.3
T_CO2_RV_in (1LKB31CT001)	°C								
position of RV (1LKB31CG001)	%	46	45	61	44	44	46	45	50
position_valve	%	100	100	100	100	100	100	100	100

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_CH2_by-pass (1LKB40CG001)									
p_CO2_HTR _p_low_side_in (1LKB42CP001)	MPa								
T_CO2_HTR _p_low_side_in (1LKB42CT001)	°C								
p_CO2_HTR _p_low_side_out (1LKB50CP001)	MPa								
T_CO2_HTR _p_low_side_out (1LKB50CT001)	°C								
p_CO2_LTR _p_low_side_out (1LKB60CP001)	MPa								
T_CO2_LTR _p_low_side_out (1LKB60CT001)	°C								
m_H2O_CH1 (1PGG20CF001)	kg/s	0.671	0.671	0.663	0.67	0.681	1.411	0.689	0.678
T_H2O_CH1_in (1PGG20CT001)	°C	15.8	16	16.3	15.8	15	18.5	14.7	17.1
T_H2O_CH1_out (1PGG30CT001)	°C	24.8	25.4	28	25.5	23.1	23.5	22	26.2

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3. Transients

In this section, 3 different transient scenarios are described and related initial/boundary conditions are given. The numerical models developed and assessed with the help of the steady-state tests will be verified in dynamic conditions, where the correct representation of the thermal capacities plays an essential role.

3.1. Loss of heat sink

The transient starts with steady state initial condition. The set of relevant initial parameters is given in Table 12.

The loss of heat sink transient is described by the drop of the mass flow in water cooling circuit (with water cooler CH1). The water cooler CH1 is the only heat sink in operation since the oil cooler is by-passed. In our case we let the water flow rate fall to 0 kg/s by switching off the water pump. After 70 s, the pump is switched on and the water flow rate start to recover back. The flow rate of the water pump is in control mode to keep the sCO2 temperature at the inlet to the MP at set value. The mass flow rate in the water cooling circuit and inlet water temperature of cooler CH1 are given in Table 13 and are displayed in Figure 9 and Figure 10 respectively. During the loss of heat sink, the inlet water temperature of the CH1 (1PGG20CT001) is influenced by the tertiary water circuit. The first small warm-up peak of the temperature 1PGG20CT001 is presumably induced by the higher sCO2 inlet temperature of the CH1 (effected by higher warm-up of the reduced mass flow rate of sCO2 which is caused by higher inlet temperature of MP, thus lower density). This rise (of the temperature 1PGG20CT001) is followed by the drop of this temperature which is induced by the sudden restart of water cooling circuit. After the second peak of the temperature 1PGG20CT001 caused by higher cooling demand (higher sCO2 inlet temperature of the CH1) leading to tertiary water circuit warm-up, the system slowly stabilizes.

The rotational speed of MP and the opening of RV are kept constant throughout the whole transient. The electrical heater H3 is switched off and H1/1, H1/2 and H2 are controlling outlet temperatures of the heaters (H1/1, H1/2 and H2). Measured values of heating power are specified in Table 13 and shown in Figure 11.

The subject of the benchmark is to provide the progress of the relevant parameters (see complete list of parameters Table 12) during the transient which will be later on compared with the measured data. The key parameters are: m_CO2_MP (1LKB70CF001), m_CO2_LTR (1LKB10CF001), p_CO2_MP_in (1LKB70CP001), T_CO2_MP_in (1LKB70CT001), p_CO2_MP_out (1LKB10CP001), T_CO2_MP_out (1LKB10CT001)

Table 12: Steady state initial parameters for Loss of heat sink transient

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Measurement type	Unit	Value
m_CO2_MP (1LKB70CF001)	kg/s	0.146
m_CO2_LTR (1LKB10CF001)	kg/s	0.146
rotational speed_MP (1LKC10CS001)	%	38.0
power_H1/1 (1LKD40CE011A)	kW	4.8
power_H1/2 (1LKD40CE011B)	kW	4.8
power_H2 (1LKD40CE011C)	kW	10.5
power_H3 (1LKD10CE011)	kW	0.0
p_CO2_MP_in (1LKB70CP001)	MPa	9.3
T_CO2_MP_in (1LKB70CT001)	°C	17.3
p_CO2_MP_out (1LKB10CP001)	MPa	19.8
T_CO2_MP_out (1LKB10CT001)	°C	27.2
position_valve_LTR_in (1LKB10CG001)	%	100.0
position_valve_LTR_by-pass (1LKB11CG001)	%	0.0
T_by-pass LTR (1LKB12CT001)	°C	20.1
p_CO2_LTR_p_high_side_in (1LKB10CP003)	MPa	19.8
T_CO2_LTR_p_high_side_in (1LKB10CT002)	°C	25.9
p_CO2_LTR_p_high_side_out (1LKB20CP001)	MPa	19.7
T_CO2_LTR_p_high_side_out (1LKB20CT001)	°C	65.0
T_CO2_HTR_p_high_side_out (1LKB30CT001)	°C	203.6
p_CO2_HTR_p_high_side_out (1LKB30CP001)	MPa	19.7
T_CO2_H1/1_H1/2_in (1LKD40CT001)	°C	204.5
T_CO2_H1/1_out (1LKD40CT002)	°C	250.0
T_CO2_H1/2_out (1LKD40CT003)	°C	250.0
T_CO2_H2_out (1LKD40CT004)	°C	300.0
p_CO2_RV_in (1LKB31CP001)	MPa	19.7

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T_CO2_RV_in (1LKB31CT001)	°C	300.3
position of RV (1LKB31CG001)	%	50.0
position_valve_CH2_by-pass (1LKB40CG001)	%	100.0
p_CO2_HTR_p_low_side_in (1LKB42CP001)	MPa	9.5
T_CO2_HTR_p_low_side_in (1LKB42CT001)	°C	273.7
p_CO2_HTR_p_low_side_out (1LKB50CP001)	MPa	9.5
T_CO2_HTR_p_low_side_out (1LKB50CT001)	°C	66.3
p_CO2_LTR_p_low_side_out (1LKB60CP001)	MPa	9.3
T_CO2_LTR_p_low_side_out (1LKB60CT001)	°C	42.5
m_H2O_CH1 (1PGG20CF001)	kg/s	0.66
T_H2O_CH1_in (1PGG20CT001)	°C	15.7
T_H2O_CH1_out (1PGG30CT001)	°C	23.5

Table 13: Mass flow rate in the water cooling circuit and heating power of electrical heaters H1/1, H1/2 and H2 during the loss of heat sink transient

t [s]	1PGG20CF001 [kg/s] Mass flow rate in water cooling circuit	1PGG20CT001 [°C] Inlet water temperature of CH1	1LKD40CE011 A [kW] Heating power H1/1	1LKD40CE011 B [kW] Heating power H1/2	1LKD40CE011 C [kW] Heating power H2
0	0.68	15.74	4.85	4.91	10.53
5	0.11	15.74	4.70	4.88	10.51
10	0.02	15.74	4.72	4.88	10.52
20	0.00	15.80	4.66	4.77	10.38
30	0.00	15.91	4.78	4.83	10.43
40	0.00	16.03	4.76	4.71	10.37
50	0.00	16.12	4.82	5.00	10.43

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60	0.00	16.17	4.63	4.78	10.37
70	1.06	16.32	4.58	4.66	9.97
80	1.18	16.32	4.38	4.37	9.66
90	1.24	16.52	4.03	4.11	9.38
100	1.17	16.35	3.82	3.83	9.21
110	1.08	16.03	3.76	3.80	9.09
120	1.04	15.83	3.91	4.06	9.11
130	0.98	15.83	3.92	4.07	9.19
140	0.96	15.80	4.11	4.06	9.36
150	0.91	15.77	4.21	4.35	9.53
160	0.89	15.68	4.23	4.35	9.64
170	0.88	15.39	4.23	4.46	9.74
180	0.84	15.08	4.38	4.33	9.94
190	0.81	14.96	4.41	4.37	9.96
200	0.79	15.16	4.48	4.61	10.13
300	0.69	16.96	4.60	4.60	10.39
400	0.68	16.03	4.72	4.72	10.24
500	0.67	15.51	4.77	4.72	10.37
600	0.67	15.74	4.73	4.95	10.46
700	0.68	15.83	4.75	4.80	10.42
800	0.69	15.74	4.63	4.72	10.51
900	0.67	15.68	4.85	4.80	10.41
1000	0.66	15.74	4.78	4.93	10.44

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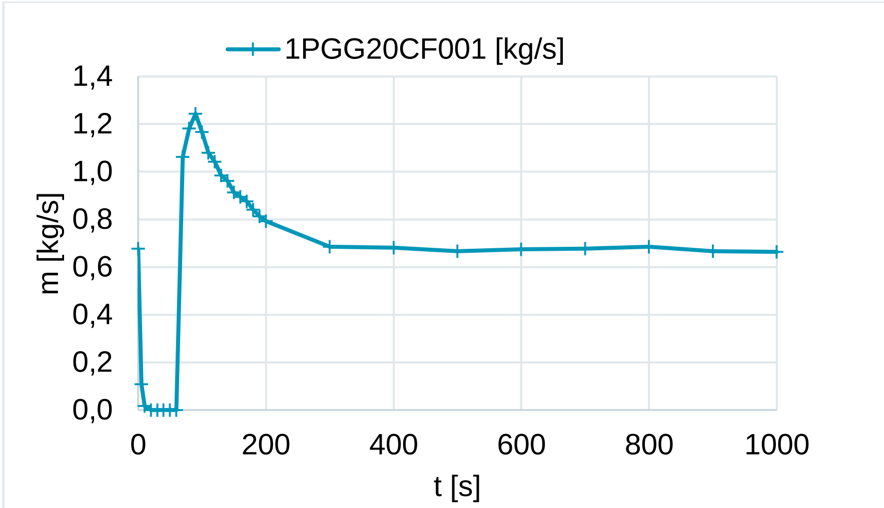

Figure 9 Mass flow rate in the water cooling circuit during the loss of heat sink transient

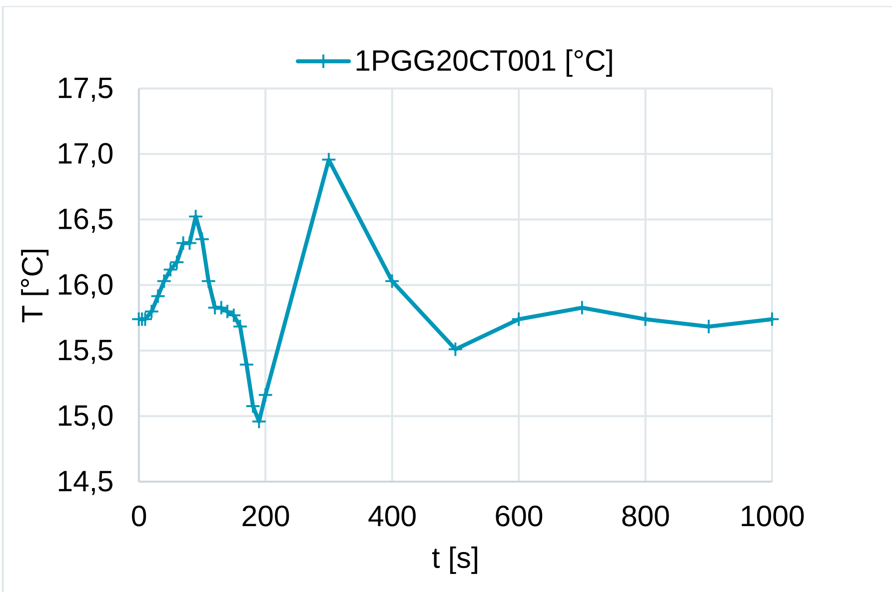

Figure 10 Inlet water temperature of CH1 during the Mass flow rate variation transient

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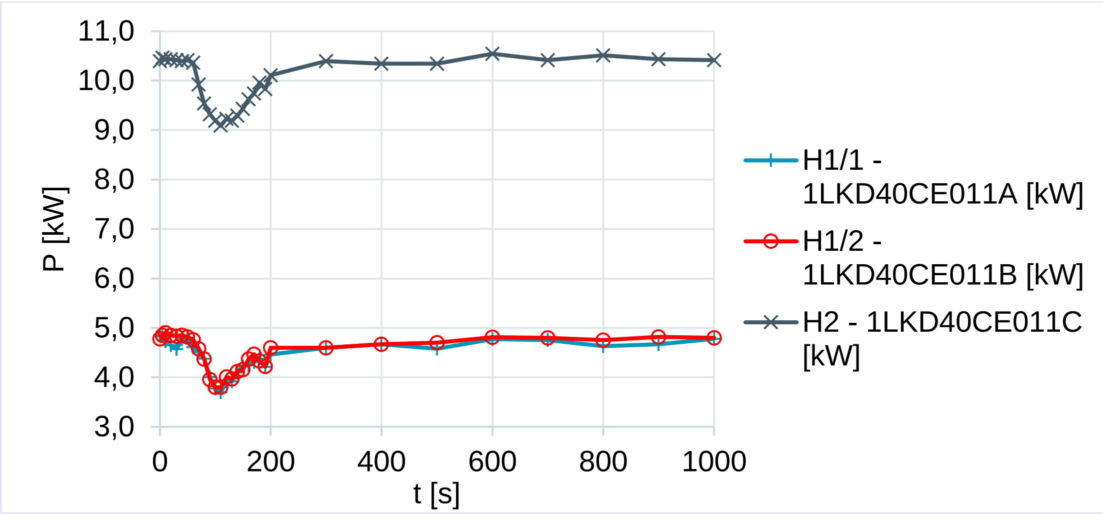

Figure 11 Heating power of electrical heaters H1/1, H1/2 and H2 during the loss of heat sink transient

3.2. Mass flow rate variation transient

The mass flow rate variation transient concerns sudden increase of the rotation speed of the main circulation pump MP from 38% to 60% within 200 s, maintaining the MP speed for about 575 s, and then sudden coast down from 60% within 200 s to its original speed at 38%. The transient started from its initial steady state conditions outlined in Table 14. The boundary condition of the transient are summarized in Table 15Table 15 and displayed in Figure 12 - Figure 15.

The course of rotational speed of MP is given in Table 15 and sketched out in Figure 12. The flow rate of the water pump is in control mode to keep the sCO2 temperature at the inlet to the MP at set value. The mass flow rate in the water cooling circuit and inlet water temperature of CH1 are given in Table 15 and displayed in Figure 13 and Figure 14 respectively. During the mass flow rate course of sCO2 (increase from the initial steady state value), the inlet water temperature of the CH1 and water mass flow rate increase due to the higher demand on cooling power (higher sCO2 inlet temperature of the CH1) leading to tertiary water circuit warm-up.

The opening of RV is kept constant throughout the whole transient. The electrical heater H3 is switched off and H1/1, H1/2 and H2 are in control mode. Measured values of heating power are specified in Table 15 and shown in Figure 15.

Table 14: Steady state initial parameters for Mass flow rate variation transient

Measurement type	Unit	Value
m_CO2_MP (1LKB70CF001)	kg/s	0.143

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m_CO2_LTR (1LKB10CF001)	kg/s	0.143
rotational speed_MP (1LKC10CS001)	%	38.0
power_H1/1 (1LKD40CE011A)	kW	8.4
power_H1/2 (1LKD40CE011B)	kW	8.5
power_H2 (1LKD40CE011C)	kW	6.4
power_H3 (1LKD10CE011)	kW	0.0
p_CO2_MP_in (1LKB70CP001)	MPa	7.8
T_CO2_MP_in (1LKB70CT001)	°C	18.3
p_CO2_MP_out (1LKB10CP001)	MPa	16.7
T_CO2_MP_out (1LKB10CT001)	°C	26.7
position_valve_LTR_in (1LKB10CG001)	%	100.0
position_valve_LTR_by-pass (1LKB11CG001)	%	0.0
T_by-pass LTR (1LKB12CT001)	°C	21.5
p_CO2_LTR_p_high_side_in (1LKB10CP003)	MPa	16.6
T_CO2_LTR_p_high_side_in (1LKB10CT002)	°C	25.6
p_CO2_LTR_p_high_side_out (1LKB20CP001)	MPa	16.5
T_CO2_LTR_p_high_side_out (1LKB20CT001)	°C	50.3
T_CO2_HTR_p_high_side_out (1LKB30CT001)	°C	231.5
p_CO2_HTR_p_high_side_out (1LKB30CP001)	MPa	16.5
T_CO2_H1/1_H1/2_in (1LKD40CT001)	°C	232.4
T_CO2_H1/1_out (1LKD40CT002)	°C	319.9
T_CO2_H1/2_out (1LKD40CT003)	°C	319.9
T_CO2_H2_out (1LKD40CT004)	°C	349.9
p_CO2_RV_in (1LKB31CP001)	MPa	16.5
T_CO2_RV_in (1LKB31CT001)	°C	350.3
position of RV (1LKB31CG001)	%	60.0

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position_valve_CH2_by-pass (1LKB40CG001)	%	100.0
p_CO2_HTR_p_low_side_in (1LKB42CP001)	MPa	8.1
T_CO2_HTR_p_low_side_in (1LKB42CT001)	°C	327.6
p_CO2_HTR_p_low_side_out (1LKB50CP001)	MPa	8.1
T_CO2_HTR_p_low_side_out (1LKB50CT001)	°C	51.3
p_CO2_LTR_p_low_side_out (1LKB60CP001)	MPa	7.9
T_CO2_LTR_p_low_side_out (1LKB60CT001)	°C	35.5
m_H2O_CH1 (1PGG20CF001)	kg/s	0.67
T_H2O_CH1_in (1PGG20CT001)	°C	15.7
T_H2O_CH1_out (1PGG30CT001)	°C	24.2

Table 15: Relative MP rotational speed, heating power of electrical heaters H1/1, H1/2 and H2, mass flow rate in the water cooling circuit and inlet water temperature of CH1 during Mass flow rate variation transient

t [s]	1LKC10CS001 [%] Relative MP rotational speed	1PGG20CF001 [kg/s] Mass flow rate in water cooling circuit	1PGG20CT001 [°C] Inlet water temperature of CH1
0	38.01	0.67	15.65
100	51.98	0.66	15.65
200	60.00	0.71	15.65
300	60.01	0.75	15.68
400	59.98	0.78	16.17
500	60.01	0.85	16.64
600	60.00	0.89	16.90
700	60.00	0.93	17.10
800	60.01	0.95	17.25
850	60.01	0.97	17.33
875	58.00	0.98	17.39

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900	41.91	0.98	17.53
1000	38.00	0.93	17.65
1100	37.99	0.86	17.25
1200	38.00	0.79	16.67
1300	38.00	0.69	16.41
1400	38.00	0.68	16.09
1500	37.99	0.67	15.68
1600	38.00	0.67	15.68
1700	37.99	0.68	15.74
1800	38.00	0.68	15.68
1900	38.00	0.67	15.65
2000	37.99	0.68	15.65

t [s]	1LKD40CE011A [kW] Heating power H1/1	1LKD40CE011B [kW] Heating power H1/2	1LKD40CE011C [kW] Heating power H2
0	8.51	8.86	6.30
100	10.38	10.18	7.53
200	11.94	11.99	8.46
300	11.85	12.05	8.58
400	11.99	12.28	8.19
500	11.59	11.87	8.19
600	11.48	11.89	8.21
700	11.53	11.95	8.17
800	11.57	11.78	8.01
850	11.63	11.74	8.16
875	11.54	11.72	8.12

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900	9.17	9.87	6.88
1000	7.98	8.17	6.01
1100	7.77	8.06	6.05
1200	7.84	7.99	6.12
1300	8.04	8.07	6.40
1400	7.99	8.14	6.15
1500	8.02	8.21	6.36
1600	8.12	8.16	6.21
1700	8.21	8.24	6.38
1800	8.19	8.39	6.43
1900	8.17	8.41	6.18
2000	8.17	8.64	6.18

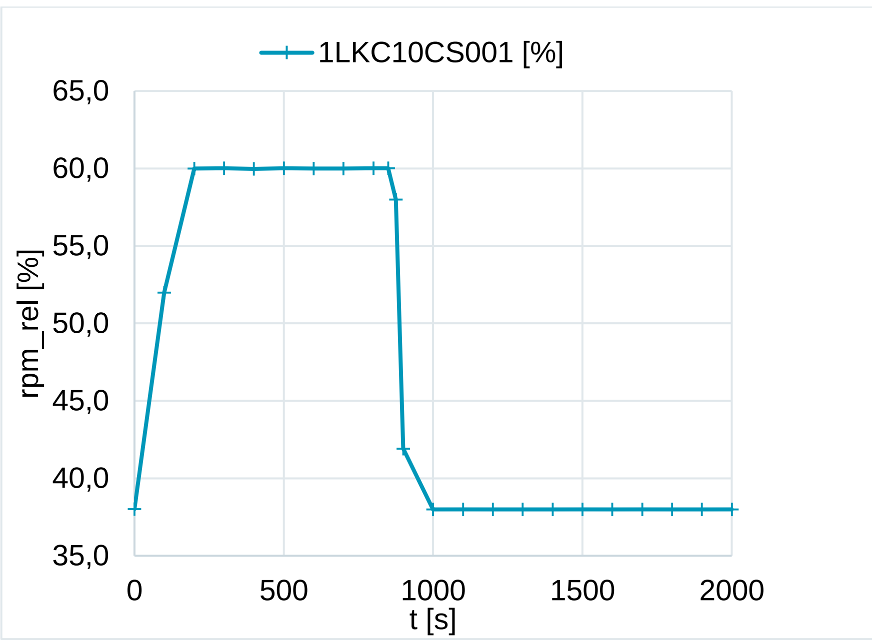

Figure 12 Relative MP rotational speed during the Mass flow rate variation transient

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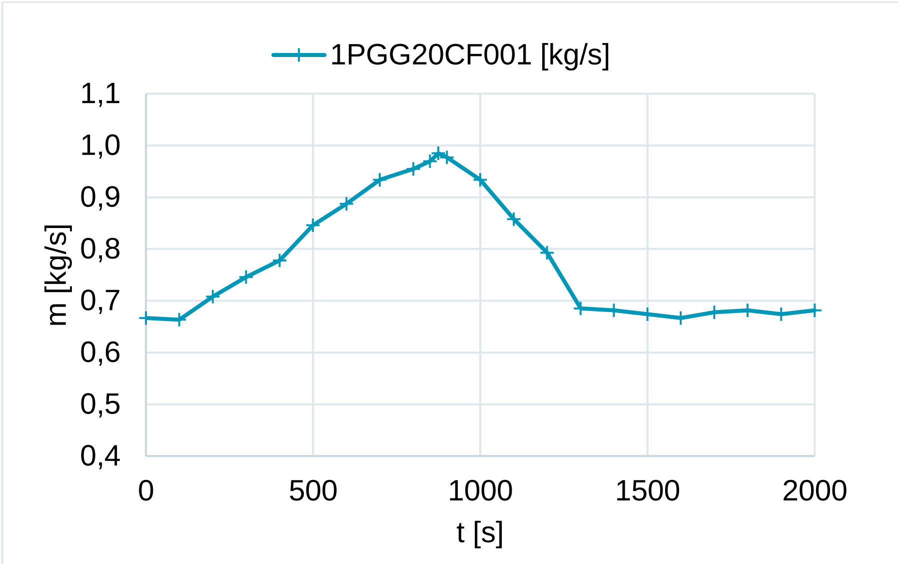

Figure 13 Mass flow rate in the water cooling circuit during the Mass flow rate variation transient

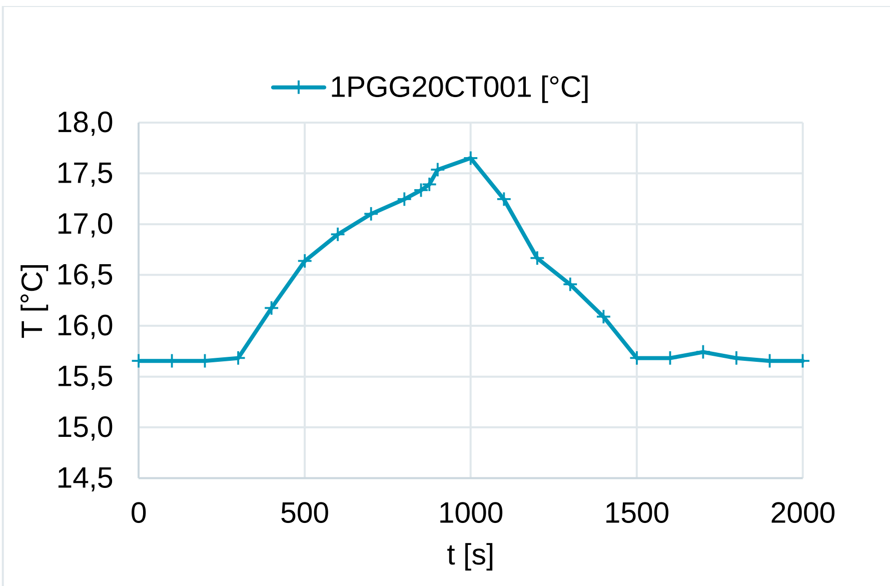

Figure 14 Inlet water temperature of CH1 during the Mass flow rate variation transient

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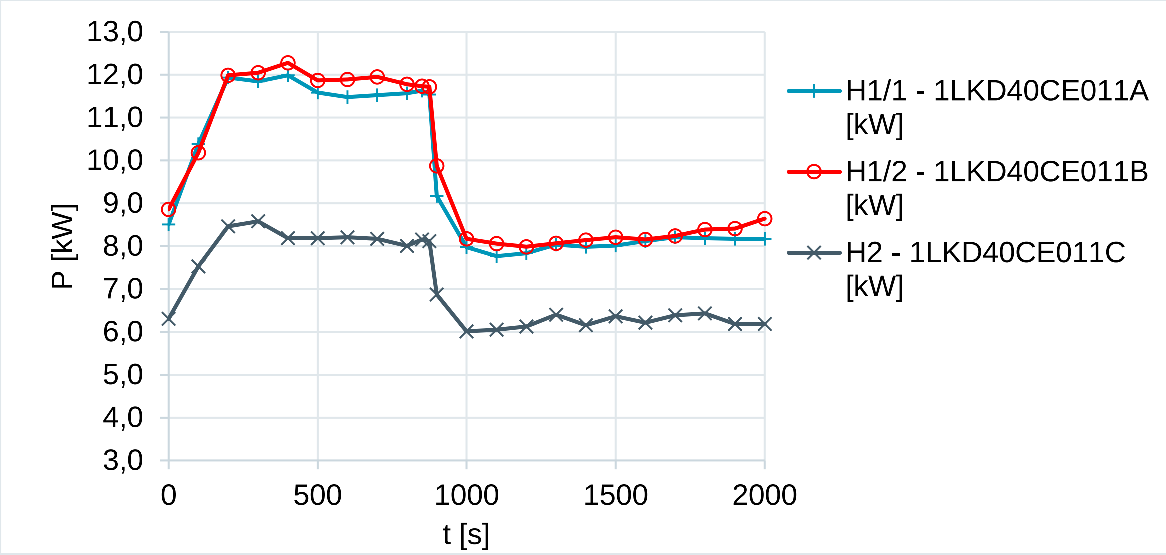

Figure 15 Heating power of electrical heaters H1/1, H1/2 and H2 during the Mass flow rate variation transient

3.3. Heating power variation transient

The heating variation transient concerns sudden increase of the electric heating power of the heater H2 21.5% (6÷7 kW) to 43% (12÷13 kW) within 3 s, maintaining the H2 heating power for about 620 s, and then sudden decrease from 43% within 3 s to its original heating power 21.5%.
The transient started from its initial steady state conditions outlined in Table 16. The boundary conditions of the transient are summarized in Table 17 and displayed in Figure 16.

The course of heating power of heater H2 is given in Table 17 and sketched out in Figure 16 together with heating power of H1/1, H1/2 which are in control mode. The electrical heater H3 is switched off. The flow rate of the water pump is in control mode to keep the sCO2 temperature at the inlet to the MP at set value. The mass flow rate in the water cooling circuit and inlet water temperature of CH1 showed constant values 0.68 kg/s and 24.15°C respectively. The opening of RV is kept constant throughout the whole transient.

Table 16: Steady state initial parameters for Heating power variation transient

Measurement type	Unit	Value
m_CO2_MP (1LKB70CF001)	kg/s	0.127
m_CO2_LTR (1LKB10CF001)	kg/s	0.127
rotational speed_MP (1LKC10CS001)	%	38.0

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power_H1/1 (1LKD40CE011A)	kW	8.4
power_H1/2 (1LKD40CE011B)	kW	8.2
power_H2 (1LKD40CE011C)	kW	6.4
power_H3 (1LKD10CE011)	kW	0.0
p_CO2_MP_in (1LKB70CP001)	MPa	7.0
T_CO2_MP_in (1LKB70CT001)	°C	19.3
p_CO2_MP_out (1LKB10CP001)	MPa	14.9
T_CO2_MP_out (1LKB10CT001)	°C	29.2
position_valve_LTR_in (1LKB10CG001)	%	100.0
position_valve_LTR_by-pass (1LKB11CG001)	%	0.0
T_by-pass LTR (1LKB12CT001)	°C	21.8
p_CO2_LTR_p_high_side_in (1LKB10CP003)	MPa	14.8
T_CO2_LTR_p_high_side_in (1LKB10CT002)	°C	27.9
p_CO2_LTR_p_high_side_out (1LKB20CP001)	MPa	14.7
T_CO2_LTR_p_high_side_out (1LKB20CT001)	°C	42.7
T_CO2_HTR_p_high_side_out (1LKB30CT001)	°C	201.9
p_CO2_HTR_p_high_side_out (1LKB30CP001)	MPa	14.7
T_CO2_H1/1_H1/2_in (1LKD40CT001)	°C	202.8
T_CO2_H1/1_out (1LKD40CT002)	°C	300.3
T_CO2_H1/2_out (1LKD40CT003)	°C	295.5
T_CO2_H2_out (1LKD40CT004)	°C	331.5
p_CO2_RV_in (1LKB31CP001)	MPa	14.7
T_CO2_RV_in (1LKB31CT001)	°C	331.7
position of RV (1LKB31CG001)	%	60.0
position_valve_CH2_by-pass (1LKB40CG001)	%	100.0
p_CO2_HTR_p_low_side_in (1LKB42CP001)	MPa	7.2

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T_CO2_HTR_p_low_side_in (1LKB42CT001)	°C	308.2
p_CO2_HTR_p_low_side_out (1LKB50CP001)	MPa	7.2
T_CO2_HTR_p_low_side_out (1LKB50CT001)	°C	43.2
p_CO2_LTR_p_low_side_out (1LKB60CP001)	MPa	7.0
T_CO2_LTR_p_low_side_out (1LKB60CT001)	°C	31.7
m_H2O_CH1 (1PGG20CF001)	kg/s	0.68
T_H2O_CH1_in (1PGG20CT001)	°C	15.6
T_H2O_CH1_out (1PGG30CT001)	°C	24.2

Table 17: Heating power of electrical heaters H1/1, H1/2 and H2, during Heating power variation transient

t [s]	1LKD40CE011A [kW] Heating power H1/1	1LKD40CE011B [kW] Heating power H1/2	1LKD40CE011C [kW] Heating power H2
0	8.46	8.23	6.43
1	8.44	8.22	7.34
2	8.67	8.46	11.87
3	8.66	8.44	12.94
4	8.59	8.39	12.90
5	8.61	8.41	12.93
105	8.61	8.43	12.90
205	8.48	8.27	12.74
305	8.52	8.34	12.84
405	8.52	8.29	12.79
505	8.52	8.29	12.79
605	8.48	8.26	12.78
620	8.47	8.34	12.80
621	8.52	8.39	12.82

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622	8.46	8.23	12.74
623	8.48	8.27	12.77
624	8.48	8.27	11.05
625	8.33	8.08	6.69
626	8.33	8.07	6.23
627	8.34	8.08	6.22
628	8.32	8.17	6.25
629	8.32	8.09	6.25
630	8.36	8.13	6.28
730	8.41	8.14	6.31
830	8.37	8.12	6.26
930	8.41	8.26	6.33
1030	8.54	8.41	6.51
1130	8.44	8.31	6.36
1230	8.46	8.26	6.38
1330	8.41	8.22	6.36
1430	8.48	8.44	6.45
1530	8.46	8.38	6.37

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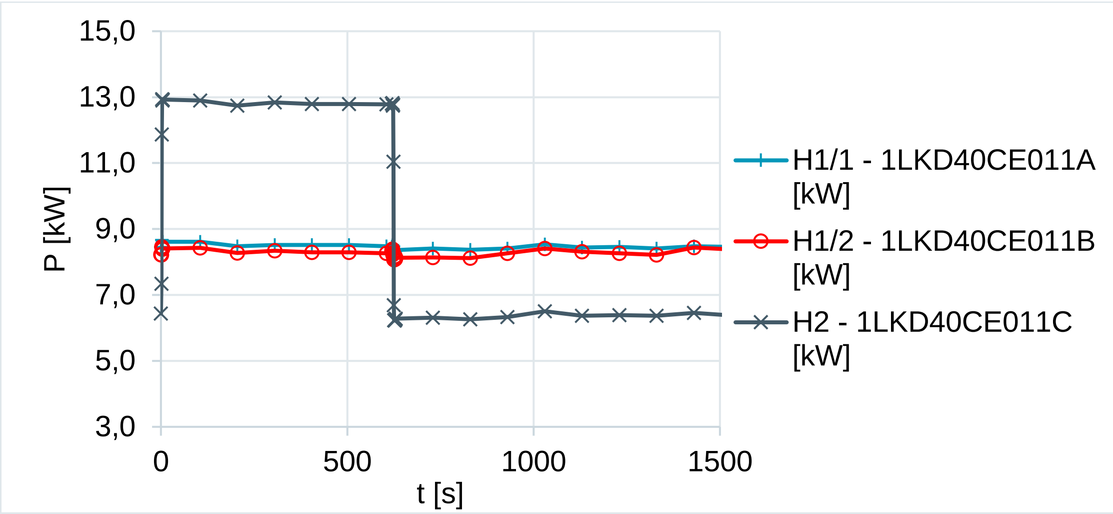

Figure 16 Heating power of electrical heaters H1/1, H1/2 and H2 during the Heating power variation transient

4. Conclusion

Set of measured steady states parameters of the sCO2 loop in CV Rez is outlined together with description of the experimental facility to the detail necessary for performing the benchmark exercise on numerical codes (Modelica based libraries). Initial and boundary conditions are defined for several steady state and transient conditions which are subject of the benchmark. The benchmark itself, including evaluation the codes for simulating, will be delivered in the upcoming deliverable D.5.10 Final report on the computational codes benchmarking.

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5. Nomenclature

Kv [m3/h]	Flow coefficient
Kvs [m3/h]	Flow coefficient at fully-open position

6. Greek symbols

λ [W/mK]	Thermal conductivity

7. Acronyms

CH1	Water cooler
CH2	Oil cooler
H1/1, H1/2, H2 and H3	Electric heaters
HP	High pressure
HTR	High temperature regenerative heat exchanger
KKS	Identification system for power plants
LP	Low pressure
LTR	Low temperature regenerative heat exchanger
MP	Main pump
P&ID	Piping and installation diagram
RV	Reduction valve

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SS	Stainless steel
SUSEN	Sustainable Energy project
TBD	To be defined
TS	Test section

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research and innovation programme under grant agreement N° 764690.

8. References

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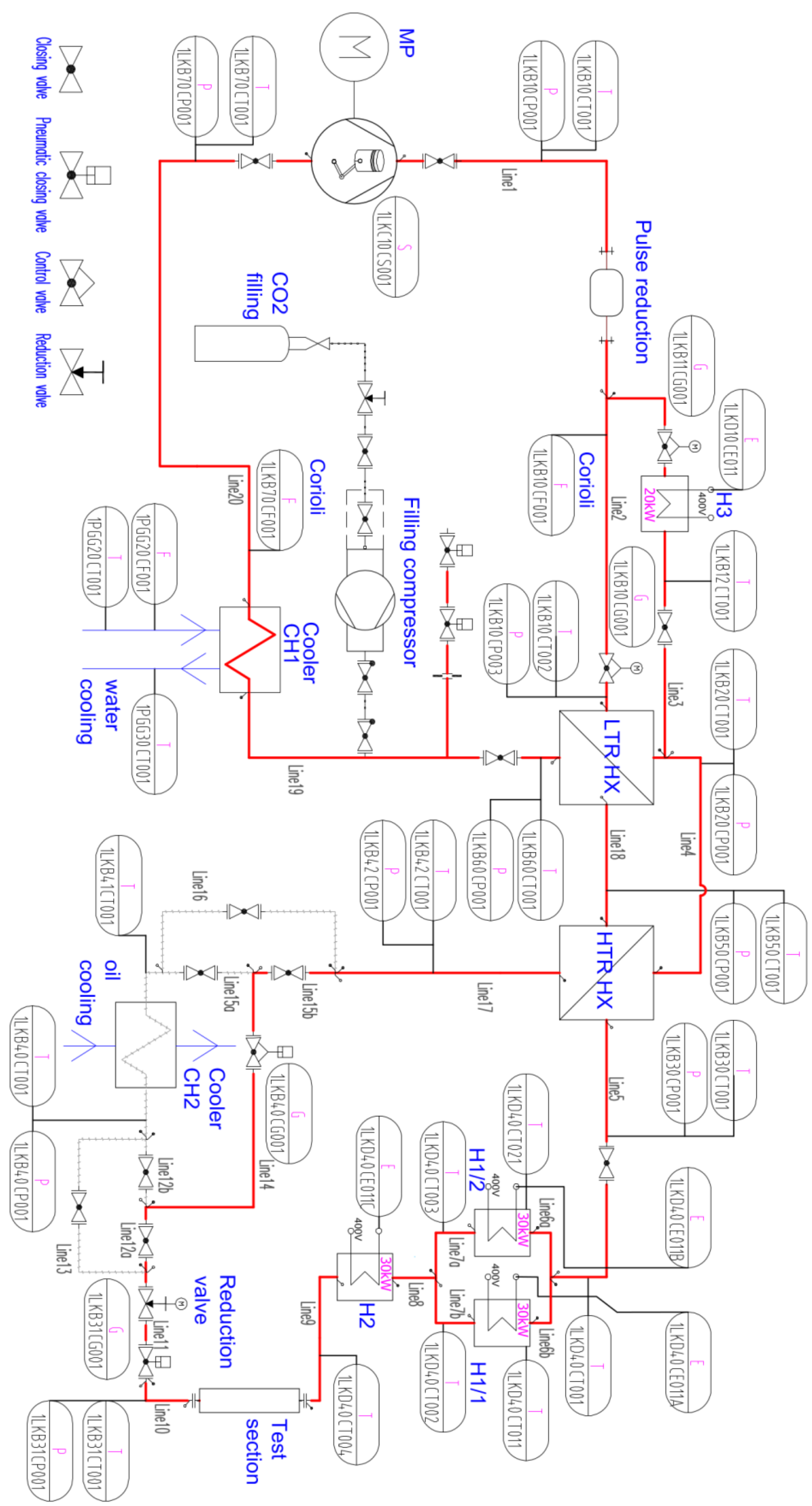
Annex 1: Piping and instrumentation diagram (P&ID) of the sCO2 loop, CV Rez



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Annex 2: Uncertainty of the measurement devices in sCO2 loop, CV Rez

Variable	Range	Unit	Description	Device error	Transducer error	Input card error	Control system error	Total error
$\dot{m}_{sCO2}$	0 - 0.7	kg/s	mass flow rate 1LKB10CF001 , 1LKB70CF00 1Rheonik (RHM12)	0.15 % from 1.66 kg/s	Rawet - PX310S 0.1 % from range	Siemens SM 331 0.4 % from range	ABB freelance 0.1 % from range	+/- 0.007 kg/s
$T_{\_sCO2}$	0 - 600	°C	TC (type K) $T_{\_sCO2}$, Omega	+/- 0.5 K for (0÷100°C) +/- 0.6 K for 300°C +/- 1.4 K for 500°C	Rawet - PX310S 0.1 % from range	Siemens SM 331 0.4 % from range	ABB freelance 0.1 % from range	+/- 4.1 K for (0÷100°C) +/- 4.2 K for 300°C +/- 5 K for 500°C
$p_{\_sCO2\_LP}$	0 - 15	MPa	sCO2 pressures at low pressure side of the loop, GE (UNIK 5000)	0.15 % from range	Rawet - PX310S 0.1 % from range	Siemens SM 331 0.4 % from range	ABB freelance 0.1 % from range	+/- 0.11 MPa
$p_{\_sCO2\_HP}$	0 - 30	MPa	sCO_2 pressures at high pressure side of the loop , GE (UNIK 5000)	0.15 % from range	Rawet - PX310S 0.1 % from range	Siemens SM 331 0.4 % from range	ABB freelance 0.1 % from range	+/- 0.23 MPa
$P_{\_H1/1-2}$ $P_{\_H2,3}$	0 - 30	kW	electric power of heaters, MT Brno	0.75 % from range	Rawet - PX310S 0.1 % from range	Siemens SM 331 0.4 % from range	ABB freelance 0.1 % from range	+/- 0.4 kW
$T_{\_water}$	0 - 120	°C	water temperature of the cooling circuit, JSP (Pt 100)	0.15K+0.2 % from range	Rawet - PX310S 0.1 % from range	Siemens SM 331 0.4 % from range	ABB freelance 0.1 % from range	+/- 1.1 K
$\dot{m}_{water}$	0 – 3.8	kg/s	water mass flow rate of the cooling circuit, turbine flowmeter, Hoffer	1.1 % from range	- -	- -	ABB freelance 0.1 % from range	+/- 0.046 kg/s

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