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OPERATIONAL EXPERIENCES AND DESIGN OF THE SCO2-HERO LOOP

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ABSTRACT

Due to its fluid properties at certain temperature and pressure, supercritical CO2 (sCO2) allows to build compact power cycles for certain applications. This characteristic of sCO2 is utilized in the sCO2-HeRo project to design a compact heat removal system as a simple Joule cycle. This paper presents the experiences and one set of measurements from these initial tests together with a description of the start-up and control strategy and procedure. The control and operation capabilities of the sCO2-HeRo loop during filling and circulation operation are qualitatively compared to those of the other two sCO2 loops (SCARLETT and SUSEN) employed within the project. The consequences of using different components in the loops on the operation are analyzed. It is pointed out that employing a filling compressor to add high-pressure CO_2 gives great operation flexibility while the use of piston accumulators may be used to stabilize cycle pressure and increase filling speed. Furthermore, if sCO2 is only required in the test section, a transcritical cycle may be used, offering faster filling and simpler control. Additionally, the paper describes the sCO2-HeRo cycle's design parameters, including detailed geometrical information and performance parameters of the assembled components required for the simulation of the loop. These may be used together with future measurement results for the validation of simulations.

INTRODUCTION

The system developed within the EU funded sCO2-HeRo project will raise nuclear reactor safety to a higher level. In case of a combined Station Blackout (SBO) and Loss of Ultimate Heat Sink (LUHS) accident scenario, it transfers the decay heat to a secondary ultimate heat sink, e.g. the ambient air (Benra et al. [1]). Due to its compactness, it can be retrofitted to existing nuclear power plants. Within the sCO2-HeRo project, a small-size sCO2 demonstrator cycle was developed and constructed at the PWR glass model at the Simulator Centre of KSG/GfS in Essen. The PWR glass model allows to simulate and visualize different accident scenarios. While the single components were already tested, the coupling of the sCO2-HeRo cycle to the glass model allows to experimentally examine the function of the sCO2-HeRo system in total and its interaction with the PWR cycle. Main objective of the system test is to proof the heat extraction from the core and to validate the operation strategy of the system. Thus, by completing the system integration tests, the system is brought to Technology Readiness Level 4 (TRL 4). The measurement results will further be used for code validation.

The presented paper describes two aspects. The first being the operation experiences made at the sCO2-HeRo loop and its comparison with the SCARLETT and SUSEN loop. These loops were used for component testing within the sCO2-HeRo project. The focus of the comparison lies on the filling and circulation of CO_2, revealing the influence of the different cycle layouts on cycle operation within these operating phases. To give a deeper understanding of the whole sCO2-HeRo cycle, the second aspect of the paper is the detailed description of the loop itself. This contains the piping and instrumentation diagram (P&I), the main components, the measurement equipment and the cycle dimensions and thus allows to use future measurement results for code (cycle simulation) validation.

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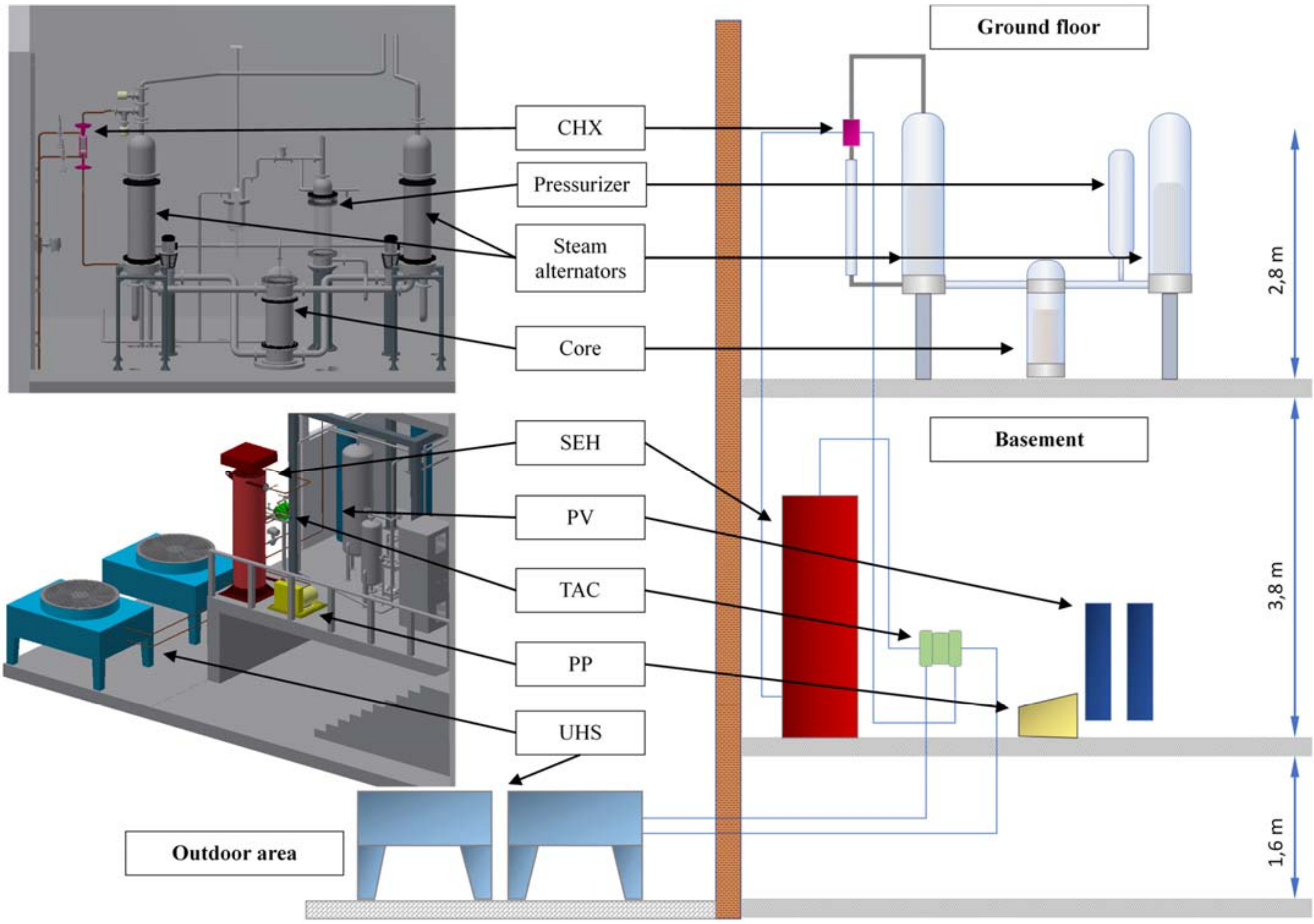

Figure 1: CAD-Drawing and component position of the sCO2-HeRo cycle

GENERAL CYCLE FUNCTION AND LAYOUT

This paragraph gives a generalized description of sCO2-HeRo cycle function and layout. The sCO2-HeRo cycle is attached to the glass model according to the scheme in Fig. 8 in Annex A (Strätz et al. [8]) with the components depicted in Fig. 1. Here, in the 3D-CAD model on the left, the components of the glass model are colored in gray and the components of the sCO2-HeRo cycle are marked with different colors. The height scheme on the right indicates the positions of the components on the three levels: the ground floor, the basement and the outdoor area. The corresponding detailed description of all components and their arrangement is provided in the second part of the paper.

In case of postulated accident scenario with sCO2-HeRo operation, valve 1, connecting the steam generator of the glass model to the heat sink, is closed and valve 2 opens establishing a natural circulation driven cooling loop on the steam side of the PWR glass model. Driven by natural convection, the steam flows upwards into the compact heat exchanger (CHX, pink), where the heat is transferred to the sCO2 side by condensation heat transfer. The condensate can be observed in a glass tube depicted in shaded blue below the CHX in Fig. 1. Through this tube it flows downwards driven by gravity and re-enters the steam generator through the feedwater line, which results in continuous heat removal from the primary circuit via the u-tubes. In the sCO2-HeRo loop downstream of the CHX a slave electrical heater (SHE, red) is installed in the basement. It provides predetermined inlet conditions to the turbine and enables transient experiments and operation of the sCO2-HeRo loop in off-design conditions. Such flexible conditions allow for operation of the sCO2-cycle close to operation boundaries without any negative feedback effect to the glass model. Downstream of the SEH, the turbine of the turbomachine (TAC, green), which consists of turbine, alternator and compressor, expands the sCO2. It then flows outside into the gas coolers of the ultimate heat sink (UHS, light blue), from which it is

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delivered to the CHX by the compressor. In the design point of the system the turbine provides more power than required for the compression leading to a self-sustaining system with excess electricity at the alternator. In the nuclear power plant, this electricity will be used for the electrical driven fans of the UHS and for different kinds of auxiliary devices. Additional to the previously mentioned components, Fig. 1 also contains the piston pump (PP, yellow) for circulation and leakage feedback and the pressure vessels, designed as piston accumulators, for the start-up procedure and compensating fluid expansion (PV, dark blue).

OPERATIONAL EXPERIENCES

This section describes the filling and circulation procedure of the sCO2-HeRo cycle as well as of the two other cycles SCARLETT (Flaig et al. [3]) and SUSEN (Vojacek et al. [10]) which were used in the sCO2-HeRo project for component tests. The cycles are constructed for different purposes and thus have different layouts and operation strategies. Their influence on the overall procedure is analyzed.

FILLING AND CIRCULATION PROCEDURE - SCO2-HERO

The sCO2-HeRo cycle was particularly designed for the system tests and consists of numerous components. Those important for the filling and circulation operation, are depicted in Fig. 2 which represents a simplification of the detailed piping and instrumentation (P&I) diagram shown in Fig. 9 in Annex B. Additional to the main components, it includes the pipe numbers (squares) and measurement numbers (circles) according to Table 3 and Table 1 respectively. The TAC is not included because it is bypassed in the circulation operation.

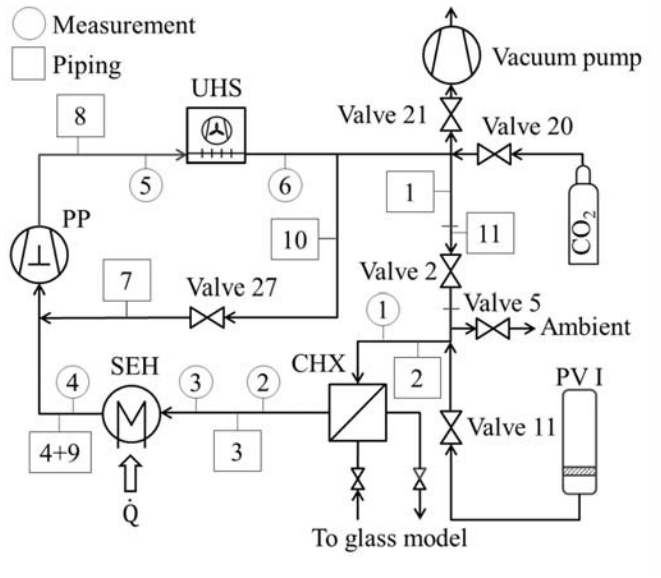

Figure 2: P&I diagram - sCO2-HeRo circulation loop

The filling procedure starts with the evacuation of the loop using the vacuum pump until a pressure of less than 0.1 bar absolute is reached. Holding the vacuum without running the vacuum pump reveals possible leakages. After evacuating the cycle, it is filled with gaseous CO_2 from the bottle. To drive the CO_2 into the cycle, the bottle is heated maintaining a driving pressure difference. The evaporation enthalpy of the CO_2 and the heating power induced to the CO_2 determine the filling speed. Valve 21 needs to be opened before evacuation and closed thereafter. Otherwise starting of the filling procedure by opening valve 20 leads to an increase of the pressure in the glass model, which uses the same vacuum pump as the sCO2 cycle. With the cycle having a volume of about 200 l without the two PV, different masses of CO_2 need to be filled to the cycle depending on the desired operation conditions. First subcritical gaseous tests required about 23 kg of CO_2 while about 30 kg will be required for initial tests with sCO2 (without PV). After filling, the cycle volume was recalculated from the CO_2 conditions and filled mass of CO_2. A comparison to the sum of volumes of the single components and piping showed good agreement, validating the volumetric cycle model. The unavoidable leakage rate (e.g. through packing glands of the valves) can be determined as long as the CO_2 is completely gaseous. In the sCO2-HeRo, it is determined to be around 5 mg/s at 40 bar and 20 °C which is related to the number of valves and connections and equivalent to a bore of a diameter of 20 µm. Note that the sealing of the PP leads to a quite large leakage rate and thus it is disconnected from the cycle in standby. Another option for filling, used to reach supercritical pressure, is to fill CO_2 directly to the PV while the valve towards the loop (valve 11) is closed. To do so the “zero-pressure” of the PV is initially set below the saturation pressure of CO_2, which lies at approximately 57 bar at 20°C ambient temperature. The pressure value determines the mass of CO_2 that is filled before reaching stationary conditions in the PV. Raising the nitrogen pressure to the desired value determines the CO_2 pressure making it liquid. This is easily possible as nitrogen in gas bottles is stored at much higher pressure as the maximum cycle pressure. It is noted that this procedure could also be applied during cycle operation. However, the required automated control and filling unit at the PV is currently not installed.

To start the circulation operation, the loop is filled up with the mass of CO_2 to reach the desired operating conditions. PV I can be employed to balance the pressure before the CHX and PP. As it is held at room temperature it may take a huge amount of CO_2. When filling of the cycle is finished, the cycle reaches steady state conditions after a certain amount of time. At this standby condition, the PP is started. If the standby condition lies within the 2-Phase region, the SEH must be turned on prior to the PP to evaporate liquid CO_2 in the SEH as the PP is designed for single phase gaseous CO_2. Considering the arrangement of the components in Fig. 1, it is evident that except for the little amount of liquid CO_2 that deposits in the SEH all liquid CO_2 will be in the UHS. This leads to two restrictions when the cycle is started. First, valve 27 may not be opened from the beginning if

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the standby conditions lead to liquid CO_2 in the UHS. Note that the temperature and thus the CO_2 conditions in the UHS depend upon the ambient temperature outside, which can be well below room temperature. Secondly, the heating power in the SEH directly after starting the PP must be sufficiently high to evaporate all liquid CO_2 coming from the UHS to avoid phase change of the CO_2 at the PP. In operation the cycle pressure is determined by PV I if valve 11 is opened. Since the volume of PV I is large, low deviations from the pre-set pressure are expected. If valve 11 is closed, there is no pressure balancing device anymore, and the pressure depends only on the filled mass of CO_2 and the temperature levels within the cycle. However, the pressure in the cycle can be reduced by releasing CO_2 via the blow off valve 5 to the ambient air (Fig. 2).

Table 1 contains the measurement results of one “cold” circulation run. During this circulation run the PP operated at full flow rate (valve 27 closed) and the heating power of the SEH was 0 kW while some heat was transferred via the CHX. Furthermore, valve 2 was fully opened while valve 11 and 27 were closed. Note that the CO_2 was cooled in the SEH because it did not reach steady state conditions due to its large thermal inertia. These measurements prove the heat transfer in the CHX and are used to validate calculated pressure losses.

Table 1: Measurements for subcritical circulating operation

Measurement position	p / bar	T / °C	$\dot{m}$ / $\frac{kg}{s}$
1	44.4	15.0	0.2
2	43.8	44.3	
3	43.0	43.7	
4	42.7	22.7	
5	48.7	34.3	
6	48.4	20.1	

FILLING AND CIRCULATION PROCEDURE - SCRALETT

Figure 3 shows a simplified P&I diagram of the sCO2 SCARLETT (**S**upercritical **Car**bon Dioxide **L**oop at IK**E** Stu**TT**gart) loop at the Institute of Nuclear Technology and Energy Systems (IKE), Stuttgart, Germany (Flaig et al. [3]).

At the start, the SCARLETT loop is evacuated by the vacuum pump and filling unit, shown on the left side in Fig. 3. Valve 1 and valve 2 are opened, valve 3 remains closed and the vacuum pump is switched on. During the evacuation it must be guaranteed that all valves in the cycle are opened to ensure that the entire loop is evacuated. The process is monitored by pressure gauges, and it is stopped after a few hours of operation until the pressure stabilizes at a value of less than 0.05 bar. Afterwards, valves 1 and 2 are closed. In the following, a CO_2 gas bottle is connected to the filling unit, and valve 2 and 3 are opened. Gaseous CO_2 is filled into the loop until a pressure of about 7 bar is reached. After closing valve 2 and 3 the CO_2 gas bottle is replaced by a CO_2 dip tube bottle which delivers liquid CO_2 through valve 2 and 3 into the storage vessel with a volume of about 120 l until a mass of about 40 kg is reached. Afterwards, valve 2 and 3 are closed, and the cycle is ready for operation. Due to saturation conditions, there is a pressure of about 57 bar (20 °C) in the entire facility, and gaseous as well as liquid CO2 exists in the storage vessel.

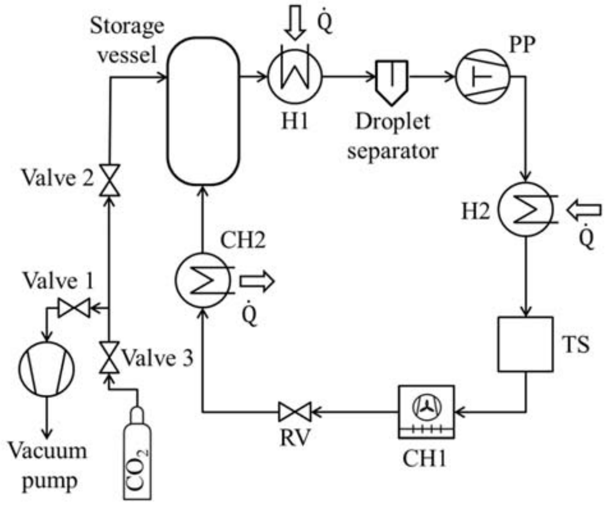

Figure 3: Simplified P&I diagram - SCARLETT loop

Before starting operation, auxiliary devices like cryostats, measurement data acquisition and the control system are switched on. At the beginning of the operation, the evaporator (H1) heats the CO_2 until a temperature difference of about 5 °C is reached between the CO_2 in the storage vessel and the CO_2 at the outlet of H1. Reaching this point, the reduction valve (RV) is closed and the piston compressor (PP) is switched on, leading to a flow of liquid CO_2 from the storage vessel through the electrical heated H1 where it is evaporated and superheated. The heating power is controlled and adjusted to ensure a CO_2 superheating of about 15 °C. After leaving the droplet separator, in which remaining liquid CO_2 droplets are separated from the flow, it enters the compressor (PP). There, the CO_2 is compressed and simultaneously compression heated, leading to a pressure increase at the high-pressure side of the SCARLETT loop. In the following, the conditioner (H2), the gas coolers (CH1) and the condenser (CH2) are switched on for the conditioning of the sCO2. After reaching a defined pressure of about 40 bar on the high-pressure side of the loop, the RV automatically increases or decreases the opening degree, controlled by the control system. In CH2 the CO_2 is completely condensed before it re-enters the storage vessel. The start-up procedure is finished when a sCO2 pressure of 80 bar and a mass flow rate of about 60 g/s is provided at the inlet of the test section (TS), when a constant superheating of about 15 °C is reached and when both controllers, the pressure and mass flow controller, are in

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operation. These controllers are used for adjusting the opening degree of the RV, the revolution speed of the PP and the cooling- or heating power of the conditioning units, leading to steady state conditions at the inlet of the TS. For all experiments to be carried out in the modular TS attached to SCARLETT, these values are the stable initial conditions which can be modified for different purposes, e.g. heating or cooling experiments.

FILLING AND CIRCULATION PROCEDURE - SUSEN

The P&I diagram of the sCO2 SUSEN loop at CVR is described in Fig. 4. The very first procedure necessary before starting-up the loop is vacuuming by means of a vacuum pump to get rid of the moisture (vacuum drying) and non-condensable gases like air. In order to intensify the cleaning technique, CO_2 is let into the loop. The desired purity is checked by sampling.

The next process is the filling. To fill the loop with the required mass to achieve operating conditions, CO_2 vapor from a standard 50 l pressurized bottle with pure CO_2 (4.5 – 99.995%), where 2 phase CO_2 is stored, is introduced just before the water cooler CH1. Hot air might be used to heat up the bottle to speed up the filling. The weight of the bottle is measured to know how much CO_2 goes into the loop. As the pressure in the system rises and approaches the pressure in the bottle, the process slows down. Hence, an air driven reciprocating filling compressor (FC) is used to speed up the filling. When a fixed mass based on model predictions gets near the normal operating mass (in our case around 40 kg of CO_2 for total cycle volume of about 95 l), the main circulation piston pump (PP) can start circulating the CO_2 content around. To increase the pressure in the system, the heaters are switched on. The maximum limit of 50 K/h temperature increase is controlled. As the system heats up and pressure rises, the mass flow rate increases as the density at the inlet to the PP increases. If further mass adjustments are needed to reach the desired parameters, the FC is used to fill the CO_2 to the loop. Reducing the pressure can be performed through opening the bleeding valves (BV) with orifices installed in the pipe. For setting the inlet temperature to the PP, the frequency of the water pump is adjusted to control the water flow rate through the CH1 cooler. The operation of the loop is controlled by the main pump speed drive. Flow rate of sCO2 is measured with a Coriolis flow meter. It is possible to adjust the flow rate through the low temperature recuperator (LTR) by-pass so to simulate a recompression cycle, as well as to adapt flow rate through the CH2 (simulating the turbine heat power release). The loop is divided into the low- and high-pressure part. The separation is performed by the reduction valve. The pressure in both parts is adjusted by the opening position of the valve.

To protect the loop against over pressure several pressure relief valves are installed at positions, where increase of pressure might occur. These are e.g. the heating parts equipped with closing valves both at the inlet and outlet as well as the pump.

The shut-down procedure is performed through the heating power control. The 50 K/h temperature change should be satisfied to bring the loop to the cold state (20°C). If there is a need for repair, the necessary part or the whole loop is evacuated trough the release valves and system of orifices to slow down the pressure change.

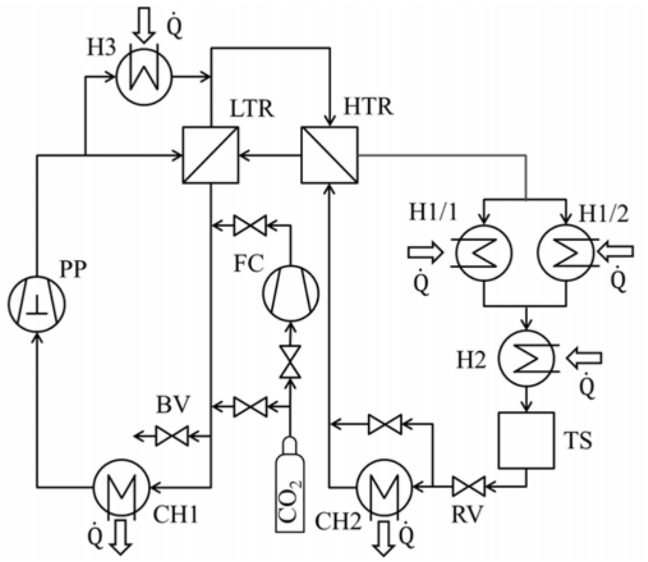

Figure 4: P&I diagram – SUSEN loop

COMPARISON

The described loops are substantially different regarding the components with effect on the operation strategy. Two aspects related to the filling and first circulation operation of the sCO2-HeRo cycle are compared to each other hereafter.

The first operation aspect is the filling of the loop. As described in the previous section filling of all loops starts by evacuating the loop to pressures below 0.1 bar. After that, the loop is filled from the bottle up to a certain pressure limit determined by the saturation pressure. The SCARLETT loop employs, different from the other two, dip tube bottles to fill liquid CO_2 to a storage tank. Compared to conventional gas bottles, this enables the filling of a higher CO_2 mass. SUSEN and sCO2-HeRo fill gaseous CO_2 directly into the loop which opens the possibility of heating up the gas bottle. The SUSEN loop allows to increase the pressure to over the saturation pressure of CO_2 by using the FC while the sCO2-HeRo loop applies the PV. Note that in this way the storage unit in the SUSEN cycle are the gas bottles which are only connected to the FC and disconnected from the cycle itself. Therefore, they do not contribute to the cycle volume. The SCARLETT loop supplies the test section with sCO2 by compressing the gas leaving the evaporator downstream of the storage vessel. The storage vessel itself is always subcritical. Thus, the SCARLETT loop is strictly speaking transcritical, and no additional filling over the saturation pressure is required. It can be concluded that the filling of the SCARLETT loop is the quickest because of its it transcritical operation requiring only saturation pressure in the storage vessel. The filling of the entirely supercritical loops SUSEN and sCO2-HeRo may require (related to the desired

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operation conditions) to add more CO_2 after saturation conditions are reached. Applying the prefilled PV in the sCO2-HeRo cycle allows to increase the pressure quicker than using the FC. However, as the vessel is primarily meant to stabilize the pressure in the cycle, the connection valve must be open after filling. Therefore, only one pressure can be set by the PV determined by careful calculation while the FC allows to set any pressure independently and is thus more flexible.

The second aspect is the dynamic setting of operation conditions in the desired test section. SCARLETT compresses the CO_2 coming from the subcritical storage vessel at stable saturation pressure with the compressor before conditioning it to the desired temperature. Pressure and temperature in the test section can be freely set by the compressor speed, the expansion valve position and the conditioning power. It is limited only by the mass in the storage vessel because increased mean density or volume of the test specimen in the sCO2 section requires additional mass to be fed. In the SUSEN loop the conditions are set, applying the release valves or FC respectively. This allows operation independent of filling conditions. The sCO2-HeRo cycle allows only one preset pressure, which relates to the selected pressure in the PV, determined by the initial filling mass of CO_2 and the preset N_2 pressure in the other chamber. The sCO2-HeRo has a release valve (valve 5), too. However, the pressure in the cycle does not change significantly as long as the PV are connected because the CO_2 mass within the PV is large and a change of pressure relates only to the movement of the piston and thus decrease of the N_2 pressure. Subsequent increase of pressure is then no longer possible because there is currently no possibility to add N_2 to the PV during cycle operation. Even with such an apparatus, the amount of CO_2 in the PV is lower after pressure reduction and increasing the N_2 pressure will only increase the cycle pressure as long as the piston in the PV does not reach the lower limit and the CO_2 part is empty. Thus, it is not possible to do large pressure variations multiple times even if the N_2 pressure is regulated during operation.

SCO2-HERO DESIGN SPECIFICATIONS

Following on the already introduced 3D-CAD in Fig. 1, the sCO2-HeRo cycle is introduced in more detail, allowing to reproduce the cycle model. This includes the complete P&I diagram, showing the arrangement of the components, the specifications of each component as well as those of the piping and measurement instruments.

PIPING AND INSTRUMENTATION DIAGRAM

The P&I diagram in Fig. 9 in Annex B represents the base of the cycle model. It includes the components of the main sCO2-HeRo system, components for start-up procedures, as well as the measurements at each location. Furthermore, it can be divided into 8 sections which are described in the following.

Section 1 is marked with red (high pressure) and blue (low pressure) pipes and depicts the components of the main sCO2-HeRo cycle, like the compressor, CHX, SEH, turbine and UHS. Furthermore, temperature (T), pressure (p), density (ρ), load (M), revolution (n), vibration (f), voltage (U), current (I) and mass flow rate (F) measurement devices as well as different kind of valves are installed.

The region marked with number 2 shows the TAC system with the frequency converter as well as the PP. The TAC is the heart of the cycle as it is the component inducing the flow and thus transporting the decay heat from the core via the CHX to the UHS. Furthermore, the turbine produces the driving force for the compressor and for the alternator from the decay heat. Therefore, it makes the system self-sustaining. The frequency converter controls the mechanical load, the revolution speed, the excess electricity and the temperature at the alternator. To reduce friction losses at the alternator and to prevent any kind of damage in the bearings of the TAC, the PP independently reduces the pressure at the alternator and bearings by drawing a defined CO_2 leakage flow from the housing of the TAC (Fig. 5). The leakage flow and pressure are adjusted by recirculating a part of the flow rate of the PP. Another purpose of the PP is the circulation of CO_2 in the cycle when the TAC is not used.

The SEH (in section 3) is required because the heat provided by the glass model via the CHX is insufficient to operate the sCO2-cycle at conditions of nuclear power plants. The heat input into the sCO2 is either realized as a constant electrical heating power or via a master slave control. Thus, the SEH allows a decoupling of the sCO2-HeRo cycle from the PWR glass model cycle for certain test cases because its heating power is sufficient to operate the sCO2 cycle without the CHX. On the other hand, in the master slave configuration, the heating power is adjusted according to the heat input from the compact heat exchanger.

The UHS is numbered with 4 in Fig. 9. Since the heat removal to the UHS is supported by electrical driven fans, voltage and current values can be adjusted and monitored to regulate the air flow and thus cooling power.

Section 5 shows the CHX. Measurement devices for measuring the pressure and temperature at the inlet and outlet of the CHX as well as for measuring the steam mass flow rate at the inlet of the CHX are installed. The two needle valves on the steam side of the CHX at the inlet and outlet are used for connecting or disconnecting the CHX from the glass model and regulating the steam flow.

The two PV are in Section 6. They are required for the sCO2-HeRo cycle to be able to start via a pressure surge. Additionally, PV II has the function of maintaining a constant compressor inlet pressure. It is assumed that in case of a start-up procedure valves 2, 4, 15, 25, 28 and 29 are open. Then, valve 11 at the bottom of PV I will be opened, and due to the adjusted pressure difference between the main cycle and PV I, the inventory is forced to flow into the sCO2-HeRo cycle. With valve 6 closed, it is heated up in the CHX and SEH before entering the turbine, where it forces the shaft to start rotating. Following on the expansion in the turbine, it flows through the

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UHS and through in the lower chamber of PV II. After reaching the breakeven point, when the compressor outlet pressure exceeds the pressure in PV I and the turbine provides more power than needed for the compressor, the start-up procedure is finished by closing the compressor bypass valve 2 to open valve 6. Then, the sCO2-HeRo system is self-sustaining closed loop operation.

Before the entire sCO2-HeRo cycle can start operation, it has to be evacuated and filled with CO_2. The vacuum pump unit for evacuation is numbered with 8 while the filling-unit consisting of a heated gas bottle and a valve is in section 7.

COMPONENT SPECIFICATIONS

The specifications of the components in the cycle, given in this section, define the capabilities of the sCO2-HeRo cycle. For reasons of limited length of the paper, only the main parameters are given. More detailed information regarding design and testing of the components can be found in the referenced papers.

TAC: The TAC was designed and manufactured by the Chair of Turbomachinery at the University of Duisburg-Essen and consists of a radial compressor with an outer impeller diameter of 40 mm and a radial turbine with an outer impeller diameter of 66 mm. Both impellers are mounted to opposite sides of one shaft. The shaft also includes the alternator in the middle and the bearings in between the alternator and the impellers (Fig. 5). All components are in one hermetic casing which is designed for a maximum pressure of 130 bar. The design rotating speed of the TAC is 50,000 rpm with a design electric power of about 7 kW. For monitoring the bearing temperatures and the vibration of the shaft, four temperature und three vibration measurement devices are installed. For more information on design of the TAC, please refer to Hacks et al. [4]. They describe the design procedure in detail and published the whole compressor geometry while Hacks et al. [5] present the first compressor performance tests and validation of the compressor performance map.

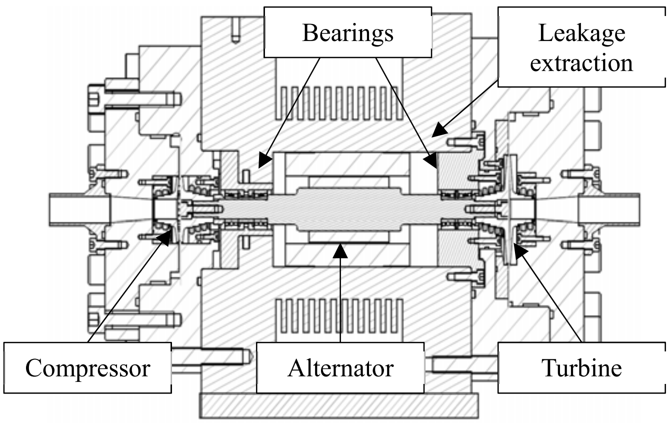

Figure 5: sCO2-HeRo TAC [4]

CHX: The CHX was designed and manufactured by the Institute of Nuclear Technology and Energy Systems (IKE) at the University of Stuttgart. The inlet conditions for the design of the CHX were derived from experimental investigations at the glass model and from sCO2-HeRo cycle calculations. In the design point of the system, sCO2 enters the CHX with a temperature of 46.8 °C, a pressure of 117.5 bar and a mass flow rate of 0.65 kg/s. A steam condensing power of 6 kW was calculated according to a steam temperature of 70.3 °C, a steam pressure of 0.32 bar and a steam mass flow rate of 2.6 g/s at the inlet of the CHX (Strätz et al. [8]).

Figure 6: Components of a compact heat exchanger with milled channels

In the following, the design of the CHX was determined under consideration of given boundary conditions, received data from single effect experiments as well as from numerical analysis. Straetz et al. [9] give a description of the single effect experiments. The counter current flow between condensing steam and sCO2 was applied because it provides the highest heat transfer capacity per surface area. The steam plate was designed with 15 straight rectangular channels with a channel width of 2 mm and a channel height of 1 mm. The wall thickness between two channels is 1.4 mm and the plate thickness is 2.4 mm. The sCO2 plate with 15 rectangular channels, a channel width of 2 mm, a channel height of 1 mm, a wall thickness of 1.4 mm and a plate thickness of 2.4 mm is quite similar. The “Z Shape” of the sCO2 channels is necessary to connect two of the four plenums with the steam side and two of the four plenums with the sCO2 side - under consideration of a stacked CHX (Fig. 6) with more than one plate on each side. The effective channel length for sCO2 is 150 mm, which is the straight length of the middle part of the channels. The entire amount of plates for the CHX is 28, with respect to a necessary transferred heat power of 6 kW and a maximum allowed sCO2 pressure drop of 0.5 bar. In addition, 14 plates with 15 channels per plate results in 210 channels on each side of the compact heat exchanger.

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SEH: The SEH was bought from Elmess Thermo System Technik and is of the type HK with a maximum electrical heating power of 240 kW. The internal DN50 piping is manufactured as a coil with an outer diameter of 590 mm and height of 2,000 mm. The internal volume is about 110 l and the maximum allowed pressure is 155 bar. A protection device monitors the temperature of the heating elements and protects them against overheating by shutdown. A controller was implemented, which is regulating the heating power according to the measured outlet temperature. The heating power is calculated from squared effective voltage of the phase angle control.

UHS: The supercritical CO_2 in the sCO2-HeRo system is cooled by means of air, hence providing heat sink to ambient for an unlimited period of time. The UHS consist of two parallel units designed as air cooled sCO2 finned-tube with the design parameters shown in Table 2. The two units are of the type GGHV CD 090.1QF/11E-31 delivered by Güntner GmbH & Co. KG. The internals of sink UHS include stainless steel AISI 304 tubes in staggered arrangement with rectangular aluminum fins (metal sheet). The arrangement is such that the flow on the sCO2 side is purely horizontal (except the inclined bends placed outside the air flow) while on the air side the flow is completely vertical. An illustrative scheme is shown in Fig. 7. Vojacek et al. [11] show a conceptual design drawing of one unit of the UHS. With an overall size of about 1.6 m in length 2.2 m in width and a height of 1.4 m each single unit features an overall heat transfer area of 361 m² and a total internal volume of 40 l including headers. More details of the geometry of the UHS are as follows. Number of tubes = 8, number of rows in depth = 6, tube diameter Ø 12 mm x 0.7 mm, number of passes = 5.5, length of one tube = 46.2 m (1.4 x 6 x 5.5 = 46.2 m), thickness of fin = 0.5 mm, pitch between the fins = 2.4 mm, staggered arrangement, pitch of tubes perpendicular to the air flow direction =50 mm, pitch of tubes above each other from the air flow sense =25 mm and pitch of tubes behind each other (diagonal) from the air flow sense =35 mm. The performance of one unit of the UHS was determined in performance test within the SUSEN-loop at CVR by Vojacek et al. [11]. They describe the test procedure and the measured cooling performance as well as internal pressure losses in detail.

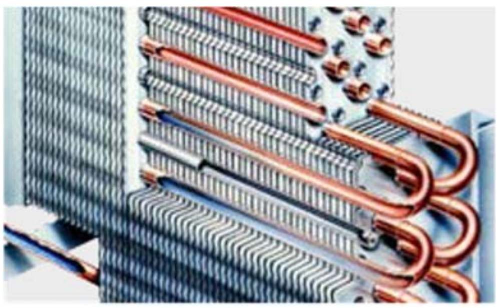

Figure 7: Illustrative picture of the internals of sink UHS including tubes with rectangular fins [2]

Table 2: Design parameters of one UHS unit [11]

Pressure of sCO2 inlet to sink UHS	78.3 bar
Temperature of sCO2 outlet of sink UHS	33 °C
Temperature of sCO2 inlet to sink UHS	166 °C
Mass flowrate of sCO2	0.325 kg/s
Thermal power of sink UHS	92.5 kW
Temperature of air inlet to sink UHS	25 °C
Temperature of air outlet of sink UHS	50 °C
Volumetric flowrate of air outlet	12500 m^3/h
Electric power of EC fans	0.33 kW

PP: The piston pump is of the type P72/225-80 III and supplied by Speck-Triplex-Pumpen GmbH & Co. KG. It has a design power of 3.8 kW at a flow rate of 120 l/min. Since it runs at a fixed speed of 260 rpm, the flow rate is adjusted by using a re-circulation of the flow via pipe 10, which is adjusted by valve 27 (Fig. 9). Its maximum pressure is 80 bar. Furthermore, it is designed for gaseous CO_2 and phase changes at the PP are prohibited.

PV: The two piston accumulators are supplied by Roth Hydraulics GmbH. The product number is AK 100-220-36. They have a nominal volume of 100 l of CO_2 each, with a design pressure of 220 bar. A piston accumulator consists of two chambers inside a cylinder, separated from each other by a sliding piston with here 360 mm diameter. Two piston accumulators are attached to the sCO2-HeRo loop, one for the high-pressure part and one for the low-pressure part. The CO_2 conditions in the lower chamber of PV I and PV II are measured with pressure gauges and Pt100. The upper chamber is filled with nitrogen with high quality. This gas works as a cushion for the mostly incompressible hydraulic fluid in the lower chamber, in this case liquid carbon dioxide. Working pressure is defined by filling the nitrogen chamber with "zero pressure", with an empty liquid chamber. By filling up the liquid chamber with fluid, the pressure of the nitrogen cushion will increase. Hence, only a fraction of the nominal volume will be used. A pressure increase from a setpoint of 70 bar by 10 bar will occur from 9.1 l liquid CO_2 at adiabatic conditions. On isothermal conditions with very slow changes in pressure, the same increase will be caused by 13.6 l liquid, starting empty at 70 bars and 20 °C. Because of this stiff characteristic, the accumulators will be used as mere buffers for temperature related expansion and for pushing the turbine for startup, but not as storage tanks for the coolant volume of the sCO2-HeRo loop.

Piping: The seamless piping is made of stainless steel of alloy-316 (1.4435). The 316 alloy is resistant in corrosive environments. The vendor Swagelok limits the pressure for ¾ inch pipes (catalogue number SS-T12-S-065-6ME, outer diameter 19 mm, with 1.6 mm thickness) to 227.5 bar (3300 psig) for a normal temperature range and 218 bar for higher

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temperatures up to 204 °C, which is well above the maximum operational pressure of 130 bar of the loop. The cross-sectional area of a typical pipe is slightly below 2 cm². Hence, with an estimated mass flow $\dot{m}$ of 0.65 kg/s and a minimum density ρ of about 100 kg/m³ after the turbine a maximum flow velocity of w=32 m/s is to be expected. Using a Moody chart (Moody, L.F. [6]) a Darcy-Weisbach friction factor of λ=0.015 results for a wide range of Reynold's numbers with an estimated roughness of 5 µm. Hence, for each meter pipe length L the dimensionless loss factor ζ can be estimated to be 0.94 resulting in a pressure loss of 0.5 bar/m. Thus, a pipe length of about 4.5 m between turbine exhaust and UHS-branching line will lead to a loss of about 2.3 bar. Losses by a check valve in this line are to be considered separately and are assumed to be in the same order of magnitude. Hence, pipe size is assumed to be sufficient. In other lines, because of lower flow velocity, only fractions of this pressure loss should be expected. The piping includes bends with large radii to avoid additional pressure losses, typically adding a loss factor ζ of about 0.13 for a 90° bend (Martin et al. [6]). Table 3 shows the different pipe lengths and number of bends in the cycle. Note that in pipe number 1 and 5 the flow is divided because of the two parallel UHS units. The pipe length is reduced accordingly to compensate the lower flow rate. Further, the pipes are not insulated.

Table 3: Piping parameters

Pipe-No.	Length / m	No. of 45° bends	No. of 90° bends	No. of elbows
1	6.6	0	10	0
2	6.6	5	1	1
3	9	1	6	0
4	1.8	0	4	0
5	4.5	0	7	0
6	1.6	0	2	1
7	2.0	1	3	1
8	1.8	0	3	0
9	3.2	0	4	0
10	1.1	1	0	0
11	0.4	0	0	2

Fittings: Pipe junctions and branches are done by fittings of Swagelok. All parts are made from alloy 316 steel. Welding was avoided, so parts can be easily remounted and mounted. As long as there is no "knee" in the pipe junction, there should be only negligible pressure loss. A knee with a sharp 90 ° turn can contribute a loss factor ζ of up to 1.3 (Martin et al. [6]). Fittings allow a maximum operational pressure to 200 bar.

Valves: Because of the fittings' compatibility, the four different kinds of valves were ordered mostly from Swagelok.

1. Ball valves with the product number SS-65TS12 with straight flow line to avoid losses are made from stainless steel of 316 type and PTFE seats. To avoid pressure hammers, these valves are mostly operated manually, e.g. to isolate components, like the piston pump. The use is limited for combination with Swagelok fittings below 190 °C because of fluoride rubber materials used for tightness.
2. Needle valves (SS18-RS12) are used to control the flow and offer the option to be equipped with a motoric drive. The flow direction within the needle valve will be changed by more than 90 ° twice, and an orifice narrows the flow path, so losses will be inevitable. In the used valves, the orifice's diameter is 9.5 mm, the Cv-Value is 1.8 (Kv = 1.56). With a flow of 0.65 kg/s at density about 500 kg/m³ (after compressor), a pressure loss of about 4.3 bar is to be expected at valve 4 (Fig. 9). On the other hand, because of closure time, pressure hammers will be avoided.
3. Check Valves (SS-CHS12-1/3) are used to avoid backflow to compressor or turbine during start-up with the PV or circulating medium with the PP. Because of materials used in the fittings, temperature is limited to 190 °C.
4. Safety relieve valves are employed to ensure limited pressure in the cycle of maximally 130 bar in the high and 113 bar in the lower pressure part.

Pressure sensors: Industrial quality ceramic membrane pressure sensors are used, adapted to the different temperature ranges and a pressure from 0 to 160 bar. Position of pressure transformers is nearby a temperature measuring, so the state of the coolant can be followed from pT-characteristics, especially in the supercritical and single-phase regions. Precision is given as +/- 0.5 % of full range, meaning +/- 0.8 bar deviation from linear behavior. Additionally, a temperature dependence of the signal must be taken into account, with no data available for the transmitters used. Typically, deviations can be about 0.3% full range (+/- 0.5 bar) for each 10 K temperature difference, even in the range of temperature compensation. Last but not least, the stability or reproducibility of the signal has to be taken into consideration, some kind of hysteresis or statistical error, which is typically in the order of 0.05 % (about +/-0.1 bar) of full range. Thoroughly measuring and numerically calibrating the different transmitters can be used to compensate non-linear effects and temperature influence. Statistical error can be estimated by repeated measuring under comparable conditions.

Temperature sensors: Temperature sensors are Pt100 resistor thermometers with Class A specification, manufactured by Electronic Sensors. This demands deviations less than 0.35 °C up to 100 °C and 0.55 °C in the range up to 200 °C. Temperature sensors for TAC bearings are type K thermocouples. There is no special necessity to precision, fast indication is needed to protect the TAC.

Flow meters: Two Coriolis type flow meters are used, PromassFP (CNGmass DCI) from Endress&Hauser. In industry, theses transmitters are designed for the use with natural gas. A mass flow between 0-1.33 kg/s can be measured in the DN15

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lines. By measuring principle from phase shift between oscillations in between the two branches of the device, mass flow is measured independently from density. The flow meters are also used to measure the density, which is especially important at the compressor inlet, which is close to the critical point, because determining the fluid properties via REFPROP is less prone to density uncertainties than temperature uncertainties. Precision relies on calibration. Deviation from calibrated values is given with 0.5 %.

Control and electrical power supply: Control of components is done by SIEMENS S7 Control Technology, with PCS7 as surface to operate and monitor. It was included to the existing parts operating the glass model. Heater control is done by JUMO phase angle control, fitted to the S7 Environment. Monitoring of CO_2 concentration and subsequent ventilation is independently realized. Shutdown of electrical power supply as protective action will be hard wired. Same is valid for overheating protection of the SEH. The electrical power for SEH can be shut off independently from other components, thus allowing operation of the sCO2-HeRo loop for commissioning purpose or tests. Because components are located outside the building, common grounding was thoroughly done to avoid differences in electrical potential.

COMMISSIONING AND SAFETY

Several safety features have been employed to safely operate the sCO2-HeRo cycle. The safety concept is checked and approved by the TÜV according to the present guidelines. First of all, access to the rooms containing the components is restricted. These rooms will not be entered in principle once a certain pressure and temperature margin is exceeded. Additionally, the rooms are equipped with CO_2 detection systems and ventilation systems, which detect leakages and warns the personnel in case the CO_2 concentration in the room gets too high. The ventilation helps to reduce the concentration quickly. Furthermore, pressure relieve valves provide safety against overpressure and fail-save safety measures against overheating of the SEH and the motor/bearings of the TAC prevent severe machine damage in case of control failure. Additionally, the vibration of the TAC is monitored and special fast acting pneumatic driven ball valve**.** protects the TAC from overspeed, bypassing the flow to the heat sink immediately.

CONCLUSION

The paper describes the general operation of the sCO2-HeRo cycle for filling and circulation procedures. These procedures are qualitatively compared with the operation of the other sCO2-cycles within the sCO2-HeRo project, namely the SCARLETT and SUSEN loop. These cycles show significantly different layouts in terms of used components. It is pointed out that filling of a transcritical cycle with a large storage vessel such as the SCARLETT loop is possible using CO_2 bottles only. The use of dip-tube bottles may allow filling in more mass more quickly. In addition, the size of the storage vessel determines the range of operation conditions within the test section due to the different mean density in the loop. Furthermore, due to saturation pressure in the vessel, it provides stable compressor inlet pressure simplifying the control of the conditions in the test section. The SUSEN and sCO2-HeRo loop apply standard CO_2 gas bottles to fill the loop. As they operate entirely in the supercritical regime, adding additional CO_2 after filling from the bottle may be required. Different approaches are the use of a FC in the SUSEN loop and PV with adjustable pressure in the sCO2-HeRo loop. It can be concluded that the change of operation conditions by control of the CO_2 mass in the cycle is more flexible applying a FC, but the PV are faster. Generally, it can be concluded that each cycle must be designed according to the according needs, and the given examples help to select a suitable approach. A first set of measurements is given in this paper, representing a simple circulation of yet subcritical, gaseous CO2, allowing a first validation of pressure losses. Further measurements will be carried out and published in the near future including stationary and transient test cases.

The second part of the paper gives a comprehensive overview of the sCO2-HeRo cycle configuration and specifications. This includes the design parameters of all main components, number and types of valves, the piping as well as measurement equipment. The P&I diagram and the height scheme present the position of all components. The referenced papers give more sophisticated information and a deeper insight in the design and testing of the components TAC, CHX and UHS.

NOMENCLATURE

D	Diameter
L	Length
$\dot{m}$	Mass flow
p	Pressure
$\dot{Q}$	Heat flow
T	Temperature
w	Flow velocity
ζ	Loss factor
η_{is}	Isentropic efficiency
λ	Darcy-Weisbach friction factor
π	Pressure ratio (total to static)
ρ	Density

ABREVIATIONS

BV	Bleeding valve
CH	Cooler
CHX	Compact heat exchanger
F	(Mass-)Flow measurement

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FC	Filling compressor
H	Heater
HTR	High temperature recuperator
LTR	Low temperature recuperator
LUHS	Loss of ultimate heat sink
p	Pressure measurement
P&I	Piping and instrumentation diagram
PP	Piston pump
PV	Pressure vessel (piston accumulator)
PWR	Pressurized water reactor
RV	Reduction valve
SBO	Station black out
sCO2	Supercritical CO_2
SEH	Slave electrical heater
T	Temperature measurement
TS	Test section
TAC	Turbomachine (turbine, alternator, compressor)
UHS	Ultimate heat sink
ρ	Density measurement

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ANNEX A

SCHEME OF THE GLASS MODEL WITH SCO2-HERO

Figure 8 shows a schematic sketch of the sCO2 cycle with the interface to the PWR glass model and valves important for operation in the glass model. Here, the CHX at the interface is denoted with PCHE in Fig. 8 and valve 2 is actually realized by two valves (valve 32 and 33, see Fig. 9) in order to completely disconnect it from the original glass model.

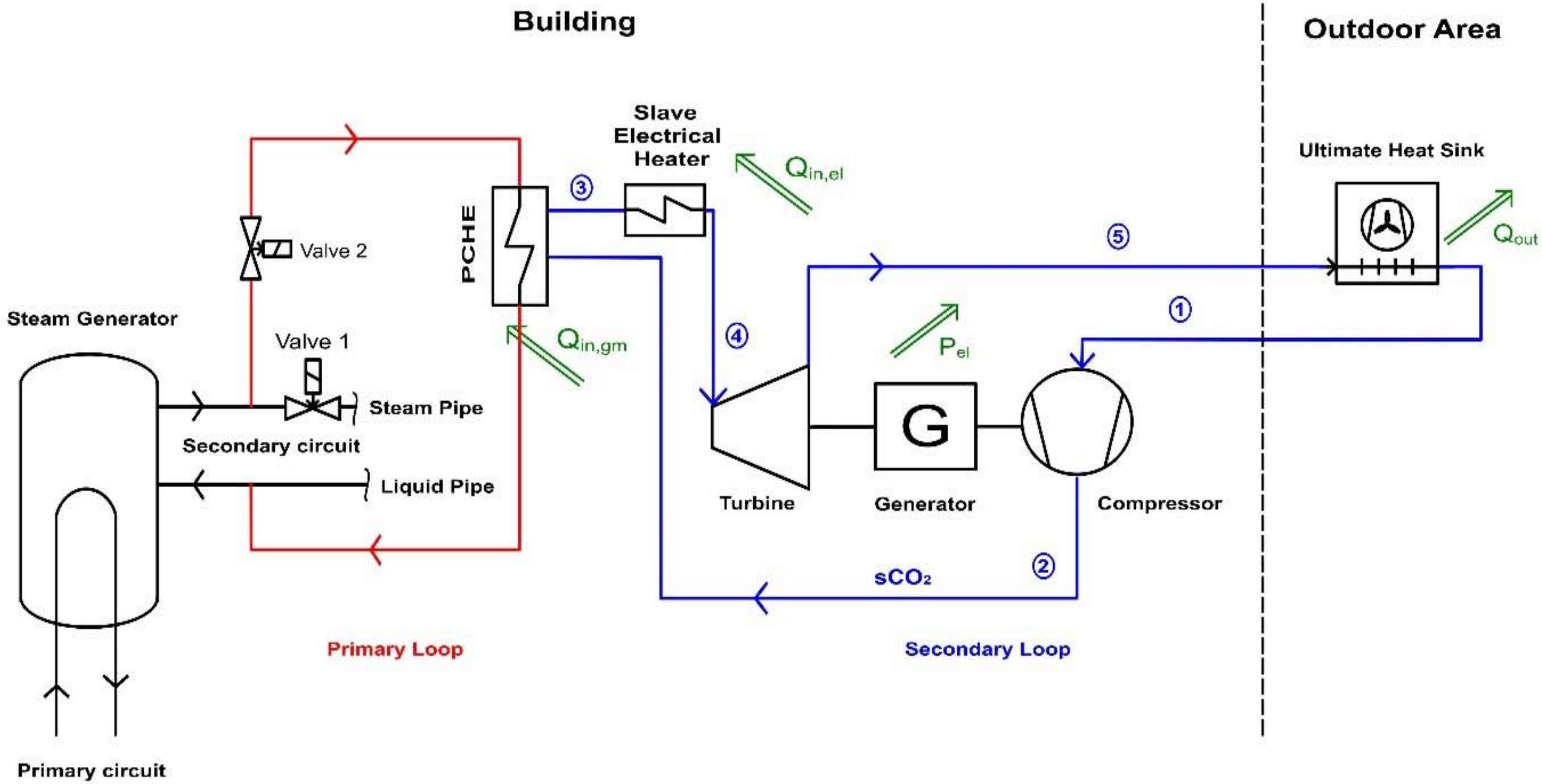

Figure 8: Scheme of the glass model with sCO2-HeRo [8]

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ANNEX B

P&I DIAGRAM OF THE SCO2-HERO CYCLE

Figure 9 shows the P&I diagram of the sCO2-HeRo cycle only. The connection to the PWR glass model, schematically presented in Fig. 8, is realized by the steam pipes in section 5.

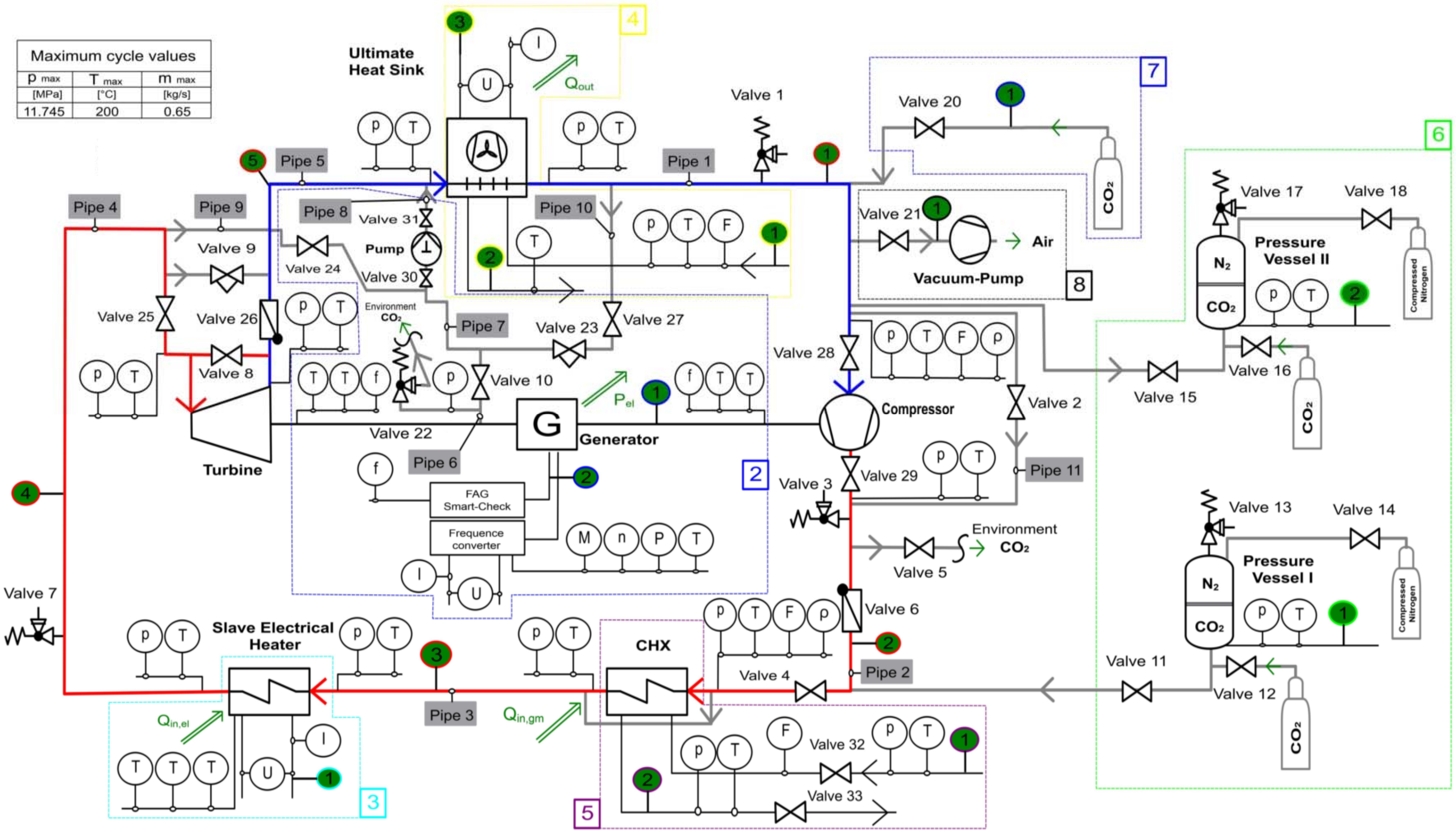

Figure 9: P&I diagram of the sCO2-HeRo cycle

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