The Supercritical CO2 Heat Removal System - Status and Outlook

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ABSTRACT

The supercritical CO2 heat removal system is a very innovative reactor heat removal concept as it improves the safety of both currently operating and future BWRs and PWRs through a self-propellant, self-sustaining and self-launching, highly compact cooling system powered by an integrated Brayton-cycle using supercritical carbon dioxide (sCO2) as its working fluid. Since this system is powered by the decay heat itself, it provides new ways to deal with beyond design accidents. The turbine of a Brayton-cycle provides more energy than necessary to drive the compressor, which means that the sCO2-HeRo system provides electricity in addition. Therefore, this system can be an excellent backup cooling system for the reactor core in case of a Fukushima-like scenario, with a combined station blackout (SBO), loss of ultimate heat sink (LUHS) and loss of emergency cooling. In addition, this system might also be used as a heat removal system for the reactor in hot stand-by condition, removing the decay heat by keeping the reactor pressure vessel at operation temperature and pressure. The system is developed within a EU funded project called "Supercritical CO2 Heat Removal System, sCO2-HeRo". The objective of this project is to build a small-size demonstrator and install it at the PWR glass model at GfS in Essen, Germany. By means of this down-scaled demonstration unit, important operational data will be gained to demonstrate the feasibility of this heat removal system.

KEYWORDS

Supercritical CO2, decay heat removal

1. INTRODUCTION

The supercritical CO2 heat removal system (sCO2-HeRo) is a novel approach to deal with Fukushima-like accident scenarios with combinations of events like station blackout (SBO), loss of ultimate heat sink (LUHS) and loss of emergency cooling. The system uses the decay heat to power a Brayton cycle with supercritical CO2 as working fluid. Since a Brayton cycle consists of a heat exchanger to the heat
source, a turbo-compressor system and a heat exchanger to the ultimate heat sink is can fulfill the safety function “removing the decay heat from the core to the diverse ultimate heat sink” and simultaneously produce electricity, which is quite valuable in the case of a station blackout, e.g. for recharging batteries or supporting fans for cooling of the CO2. Venker et al. [1-6] have studied the feasibility of this decay heat removal system with supercritical CO2 (sCO2) as working fluid using the German thermal-hydraulic code ATHLET. For a boiling water reactor (BWR) the simulation results have shown that such a system has the potential to enlarge the grace time for interaction to more than 72 hrs. Figure 1 shows the Brayton cycle attached to a BWR. In case of an accident the containment isolation valves will be closed and the safety valves (SV) will open. The steam flows into a heat exchanger (CHX), which must be very compact to fit into the limited space available in existing reactors. Inside the CHX the carbon dioxide is heated up. It flows through a turbine which is located on the same shaft like the compressor and generator. Downstream of the turbine, the supercritical CO2 is cooled by means of air and is delivered to the compressor and to the compact heat exchanger. Since the turbine of the Brayton cycle produces more power than the compressor needs to operate, the excess power is transferred into electricity, in Figure 1 used to power additional fans for better heat removal. Because of similar steam parameters of a BWR and of the steam generator of a PWR, from the thermodynamic point of view, this system can be attached to both existing PWRs and BWRs.

Fig. 1: Schematic Sketch of the Turbo Compressor System [4].

However, the ATHLET results are based upon best estimates and must be validated with suitable experiments. Within the EU funded project “sCO2-HeRo”, six partners from three European countries are working on the assessment of this innovative decay heat removal system. The goal is to investigate the technical potential of this system and to build up a small-scale demonstrator (technology readiness level (TRL) 3) at the PWR glass model at GfS, Germany [7].

1.1. Strategy

The strategy to approach can be derived from the requirements for TRL-3. According to the definition of the European Commission TRL-3 means “Experimental proof of concept [8]. A more pronounced explanation is given by the US DoD [9]: “Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.” Within the sCO2-HeRo project, a stepwise approach is applied, see Figure 2. Based upon the coarse design by Venker [1], simple models for the heat exchangers and for the turbo-compressor system have been derived and implemented into the ATHLET code. These models will be validated by means of dedicated experiments. On a small-scale these experiments include heat transfer and pressure drop tests for plates of compact heat exchangers, and single component tests. With component tests available a small scale-demonstrator will be built to be attached at the PWR glass modell at GfS, Germany. This
glass model is used for education and training of operators of nuclear power plants. Thermohydraulic phenomena and general plant behavior can be simulated, which include also severe accident conditions. The small scale demonstrator will be attached to one steam generator and take over the cooling function in simulated events like “loss of ultimate heat sink” and “loss of emergency core cooling”. Valuable information will be gained from these experiments, e.g. the interaction with the heat removal system and the primary loop. Valuable operational data so-called “learning curves” will be derived, e.g. control strategy of the sCO2-HeRo and operation limits.

Finally demonstrator experiments will be carried out for validation of heat transfer or pressure drop models. The validation results and test results will be transferred afterwards to component models on power plant scale to be implemented into the ATHLET code. With these data available predictive ATHLET simulations will be carried out to evaluate to potential of this heat removal system. As a next step (beyond the scope of this project), the data must be validated on relevant scale and relevant environment (TRL-5 to TRL6).

2. COMPONENT TESTING

In order to bring the systems on TRL-3 component tests are necessary for validation. Before assembling the sCO2-HeRo demonstrator system in the GfS, each major component was tested in different institutions. The performance of the CHX was verified in the sCO2 test loop (SCARLETT) in University of Stuttgart, while the air-cooled sink HX, compressor and turbine were measured in the CVR sCO2 experimental facility. The turbo-compressor was designed at University of Duisburg Essen and tested in the CVR sCO2 experimental facility.

2.1. Compact Heat Exchanger

The experimental investigation on the heat transfer between condensing steam has been separated into two stages: 1) 0.32 bar, 286°C and 2) 70 bar, 286 °C) on the steam side. The 0.032MPa test have already been reported by Streatz [10]. Their purpose is to test a pair of heat exchanger plated for glass model conditions. After finishing these experiments the condensation and consequently the heat-up of the sCO2 must be investigated for power plat conditions (7MPa, 286 °C). For both campaigns in the SCARLETT
test facility of IKE, University of Stuttgart. The test configuration consists of the SCRALETT loop [11], which provides sCO2 under defined conditions, and a high pressure steam cycle [12]. Both are schematically shown in the piping and instrumentation (P&I) diagram in Fig. 3.

The high pressure steam cycle is described in more detail (marked in red). At the beginning a storage vessel (1) is filled with deionized water. During operation the water is pumped from the storage vessel by a high performance liquid chromatography pump (3) (HPLC) through a filter (2) into an electrical heated evaporator (4). There the water is evaporated and slightly superheated before the steam flows into a test section (5). In the test section any kind of component can be installed, e.g. a diffusion bonded two-plate CHX. The pressure in the high pressure steam cycle can be adjusted by the mechanical primary pressure control valve (6). After the expansion in the pressure control valve the condensate flows into the storage vessel (7). For monitoring the fluid and steam properties in the cycle, measurement devices like resistance thermometers Pt 100 (T), pressure gauges (P) and a mass flow meter (ṁ) are installed. The position and nomenclature of each measurement device is shown in the P&I diagram in Fig. 3. For example, T01 is the resistance thermometer at the inlet of the electrical heated evaporator and P03 is the pressure gauge at the outlet of the two-plate CHX test section.

The pressure in the steam cycle can be adjusted from about 1 bar to 105 bar and the corresponding steam temperature is rising from about 100 °C to 315 °C. The water volume flow rate can be varied by the HPLC pump (3) from 0.05 l/h to 2.5 l/h. The installed electrical heating power of the evaporator (4) with 1.6 kW is high enough for evaporation and superheating the adjusted water volume flow rates.

The SCARLETT loop (marked in green) is able to provide a sCO2 mass flow rate \( \dot{m}_{\text{sCO2}} \) from about 30 to 110 g/s. The achievable mass flow rate depends on the compressor performance map, which leads to less mass flow rate at higher pressures and vice versa. The sCO2 temperature at the inlet of the test section T06 can be varied by conditioning from about 0 °C to 40 °C and the pressure P04 can be adjusted from about 75 bar to 110 bar.

The measurement parameters for the investigation on the heat transfer between the high pressure steam side (70 bar) and the sCO2 side in the two-plate CHX are summarized in Table 1. Six measurement campaigns were carried out in which different inlet conditions on both sides (H2O and sCO2) of the two-plate CHX were used to receive experimental results of the heat transfer performance under “design point” (DP) and “Out of the design point” (ODP) conditions. It should be mentioned, that the measurement parameters for the DP and ODP experiments were derived from investigations at the glass model [6] and from internal restrictions at the test facilities.
Table 1: Measurement campaigns of the two-plate CHX

<table>
<thead>
<tr>
<th>Campaign</th>
<th>$P_{\text{CO}_2, \text{in}}$ - P04 [bar]</th>
<th>$T_{\text{CO}_2, \text{in}}$ - T06 [°C]</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>110</td>
<td>40 (44.5)</td>
<td>Design Point</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>40 (41.3)</td>
<td>“DP”</td>
</tr>
<tr>
<td>3</td>
<td>95</td>
<td>39.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>40 (44.5)</td>
<td>Out of Design</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>40 (41.3)</td>
<td>Point</td>
</tr>
<tr>
<td>6</td>
<td>95</td>
<td>39.5</td>
<td>“ODP”</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_{\text{CO}_2}$ [g/s]</th>
<th>$m_{\text{H}_2\text{O}}$ [l/h]</th>
<th>$Q_{\text{Evap}}$ [W]</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>0.65</td>
<td>460</td>
<td>DP</td>
</tr>
<tr>
<td>56</td>
<td>0.80</td>
<td>560</td>
<td>DP</td>
</tr>
<tr>
<td>68</td>
<td>0.97</td>
<td>680</td>
<td>DP</td>
</tr>
<tr>
<td>37</td>
<td>0.65</td>
<td>460</td>
<td>ODP</td>
</tr>
<tr>
<td>37</td>
<td>0.80</td>
<td>560</td>
<td>ODP</td>
</tr>
<tr>
<td>37</td>
<td>0.97</td>
<td>680</td>
<td>ODP</td>
</tr>
<tr>
<td>37</td>
<td>1.17</td>
<td>830</td>
<td>ODP</td>
</tr>
<tr>
<td>37</td>
<td>1.43</td>
<td>1010</td>
<td>ODP</td>
</tr>
<tr>
<td>37</td>
<td>1.74</td>
<td>1230</td>
<td>ODP</td>
</tr>
</tbody>
</table>

In the DP experiments according to campaign 1, 2 and 3 the sCO2 mass flow rates $m_{\text{CO}_2}$ from 46 g/s to 68 g/s correspond to the water volume flow rates $m_{\text{H}_2\text{O}}$ from 0.65 l/h to 0.97 l/h. The power of the electrical heated evaporator $Q_{\text{Evap}}$ was adjusted according to the water volume flow rates from 460 W to 680 W. To investigate the heat transfer capacity also ODP, measurement campaign 4, 5 and 6 were carried out. Therefore, a constant sCO2 mass flow rate $m_{\text{CO}_2}$ of 37 g/s and gradually increasing water volume flow rates $m_{\text{H}_2\text{O}}$ from 0.65 l/h to 1.74 l/h were used. The power of the electrical heated evaporator $Q_{\text{Evap}}$ was adjusted according to the water volume flow rates from 460 W to 1230 W. To investigate the heat transfer behavior additionally with different sCO2 inlet pressures P04, thermodynamic cycle calculations were carried out for the sCO2-HeRo system to determine the sCO2 inlet temperatures T06 into the CHX. The results have led to a temperature of T06 = 39.5 °C for P04 = 95 bar, T06 = 41.3 °C for P04 = 100 bar and T06 = 44.5 °C for P04 = 110 bar. Considering the internal restrictions of the SCARLETT test facility, the maximum sCO2 inlet pressure was determined to P04 = 110 bar and the inlet temperature to T06 = 40 °C.

An example of the heat balance results are given in Fig. 4 for a CHX with 2x1 mm channel dimension.

Fig. 4: Heat transfer between cCO2 and H2O [12]
In Fig. 4, the heat input into the sCO2 $Q_{\text{sCO2}}$ is plotted as a function of the condensing power of the steam $Q_{\text{H2O}}$. Verify that the condensing power of the steam was reliably transferred to the sCO2 side for all measurement campaigns, under consideration of thermal losses and measurement uncertainties with an offset of 85 W.

2.2. Turbo-Compressor System

The turbomachine has an integral design with turbine, alternator and compressor (TAC) together on one shaft in the same casing. The cross section of the machine and pictures of the impellers with dimensions are shown in Fig. 5. The impellers are shrouded to allow the application of labyrinth seals for reduction of leakage losses. Further the shrouded design allows larger axial clearances and thus more axial displacement due to e.g. thermal expansion. This increases robustness of the TAC and the safety system. As the demonstrator cycle has the same temperatures as the full-scale system but substantially lower heating power, the mass flow is very small. Thus, the blade height is also very small, raising challenges for manufacturing. The small mass flow and the sCO2 properties also cause challenges in general choosing of the operating point. As the machine theoretically allows hermetic design, the pressure and thus density and windage losses are large. At the speed of the optimum compressor operating point they become so large, that they exceed the turbine power. As a compromise the rotational speed is reduced. The basic design parameters are a mass flow of 0.65 kg/s with an inlet temperature of 33 °C and 200 °C at the compressor and turbine inlet respectively. The inlet pressure to the compressor is 78.3 bar and the design pressure ratio is 1.5. The shaft rotates at 50,000 rpm and produces 7 kW of electrical power. For further information on the design please refer to Hacks et al. [14].

First component tests on the TAC are carried out in the sCO2 test loop at Research Centre Řež (CVR), Czech Republic. The tests are used to validate the calculated TAC performance and to gain experience on the TAC start-up and operation behavior. The tests are focused on the compressor performance. For start-up the cycle is brought to supercritical conditions using a circulation pump. Then the shaft of the TAC is accelerated by the alternator used as a motor. Different acceleration rates are tested and the behavior of the machine is monitored. It is found that these rates can be large at low speed but must decrease with increasing speed. The performance of the compressor is measured by monitoring the inlet and outlet conditions regarding temperature and pressure. The results are then compared to the previous CFD calculations presented by Hacks et al. [14]. The measured pressure ratio shows good agreement.
with the calculations, which lie within the uncertainty range of the measurements. A more detailed discussion of the measurement results is given by Hacks et al. [15].

2.3. **Heat Exchanger to Ultimate Heat Sink**

The heat transfer investigations in the air cooled sCO\textsubscript{2} finned-tube Ultimate Heat Sink (UHS) test configuration took place at CVR. Fig. 6 shows the experimental set up.

![Fig. 6: The Ultimate Heat Sink with measurements.](image)

The nominal thermodynamic parameters of the UHS are shown in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure of sCO\textsubscript{2} inlet to sink HX</td>
<td>7.83 MPa</td>
</tr>
<tr>
<td>Temperature of sCO\textsubscript{2} outlet of sink HX</td>
<td>33.0°C</td>
</tr>
<tr>
<td>Temperature of sCO\textsubscript{2} inlet to sink HX</td>
<td>166.0°C</td>
</tr>
<tr>
<td>Mass flowrate of sCO\textsubscript{2}</td>
<td>0.325 kg/s</td>
</tr>
<tr>
<td>Thermal power of sink HX</td>
<td>92.5 kW</td>
</tr>
<tr>
<td>Temperature of air inlet to sink HX</td>
<td>25.0°C</td>
</tr>
<tr>
<td>Temperature of air outlet of sink HX</td>
<td>50.0°C</td>
</tr>
<tr>
<td>Volumetric flowrate of air outlet</td>
<td>12500.0 m\textsuperscript{3}/h</td>
</tr>
<tr>
<td>Electric power of EC fans</td>
<td>0.33 kW</td>
</tr>
</tbody>
</table>

The overall heat transfer area for the UHS is 361 m\textsuperscript{2}. The detail geometry of the UHS is as follows. Length = 1.4 m, width = 2.2 m, number of tubes = 8, number of rows in depths = 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 measurement campaigns covered both supercritical and subcritical regions including transition through the pseudocritical region in the last stages of the sink HX. The critical point of the CO\textsubscript{2} is 7.39 MPa and 31.1°C.

The results of calculated averaged overall heat transfer coefficients using correlations (Gnielinski [16] for sCO\textsubscript{2} and VDI [17] for the air) and experimentally determined values shows for the performed tests reasonably low error of + 25 % and − 10 %. Hence, using the correlations for the estimation of the heat transfer in the UHS with a similar design and similar conditions gives a fair error and thus is
recommended. More detailed discussion of the performance is presented in the paper of Vojacek et al. [18].

3. INTEGRATION INTO GLASS MODEL

After testing of the components in the SCARLETT Facility at University of Stuttgart, Germany and in the SUSEN Loop at Research Centre Rez, Czech Republic, they were shipped to GfS for installation. The glass model of a pressurized water reactor (PWR) is located at the Gesellschaft für Simulatorforschung GfS in Essen, Germany [19]. It is a small-scale demonstration facility of a two-loop PWR in the scale 1:10 made of glass. During training and education lectures, e.g. for NPP personnel, it is used as a visualization device for thermal-hydraulic behaviour in the core, in steam generators and the piping. Complex thermal hydraulic phenomena in the system are demonstrated during normal plant operation and under accident conditions. The main components of the glass model are shown in Figure 7a. It includes the electrically heated reactor pressure vessel (in the centre), two steam generators (left and right hand side), the pressurizer (in the background centre), glass piping for the primary as well as for the secondary circuit, measurement devices and valves. The glass model was modified such that an extra bypass pipe was installed at one steam generator. It connects the steam volume via the compact heat exchanger with the liquid volume of the steam generator. Figure 7b shows the CHX marked with a red box.

![Glass model at GFS Essen (a) and compact heat exchanger (b) attached to one steam generator](image)

Figure 8 shows the set-up of the sCO2-HeRo to be installed, which is quite similar to Figure 1. In case of accident simulation, the connection of one steam generator to the ultimate heat sink is shut off by closing the solenoid valve 1. Driven by natural convection, the generated steam flows through the solenoid valve 2 into the compact heat exchanger (CHX), where it is condensed. From there the coolant flows back into the steam generator driven by gravity. In the CHX, the sCO2 is heated (3). A slave electrical heater is rising the sCO2 temperature to about 200°C (4). This slave electrical heater is necessary, because the operation pressure of the steam generator in the glass model is 0.032MPa (saturation conditions) and due to that the steam temperature is too low (about T = 70°C) for the turbine. A CO2-turbine working at 70°C would be so tiny that manufacturing difficulties prevent to build a suitable turbomachine in this early stage of the sCO2-HeRo project. Therefore, it was decided to increase the sCO2 temperature up to a similar level which can be expected in a power plant application. Summarizing, the heat-up process of the sCO2 is performed in two steps. In the first step, the sCO2 is heated up through condensing steam in the CHX, followed by a “conditioning” to suitable turbine inlet temperatures in the slave electrical heater. This slave electrical heater will not be used in power plant scale application.
Fig. 8 Glass model setup for the sCO2-HeRo demonstrator.

The installation of the sCO2-HeRo system is currently carried out. The first commissioning tests will be carried out in early summer 2018. The first test cases will be performed starting in July 2018.

3.1. Test Procedure

A number of test cases will be carried out to evaluate the performance of the sCO2-HeRo system. As derived by Hajek, Table 3 shows an extraction of the test procedures to be carried out.

Table 3: Test procedure to evaluate the performance of the small-scale sCO2-HeRo system.

<table>
<thead>
<tr>
<th>Test</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commissioning tests</td>
<td>Individual tests of each equipment and electrical power and control systems must be verified. Manoeuvrability armatures will be verified.</td>
</tr>
<tr>
<td>Pressure tests</td>
<td>Tightness and strength pressure tests will be performed at the beginning of commissioned system. The proof of safety of pressurized equipment will be conducted by an authorized person.</td>
</tr>
<tr>
<td>Filling of the device</td>
<td>The capability of the system to be filled from external CO₂ sources up to the required pressure level or required amount of CO₂ in the loop, depending of chosen start up strategy, must be verified. In addition, the ability of the auxiliary system to maintain constant pressure and amount of CO₂ within the loop must be verified. Control of CO₂ amount is necessary.</td>
</tr>
</tbody>
</table>
| Start-up              | The test of the start-up system will be very important. Depending on start-up strategy, the ability of the proposed system to provide self-launching starts must be tested.  
In case of a self-launching start providing CO₂ from a large volume upstream of the heat source, the ability of control system must be verified according to the following conditions:  
• respond to the demand to start  
• supplement the necessary amount of CO₂ and discharged the same  
• evaluate achievement of self-propellant state  
• transition all valves to the operational mode  
• capability of self-regulation  
• control all parameters to be consistent with nominal operation parameters. |
### Test Parameters

In case of a self-launching start procedure using the generator to bring the turbomachine to operational speed the ability of control system must be verified according to the following conditions:

- respond to the demand to start
- start filling procedure to reach CO\(_2\) loop content at the operational level from standby conditions (CO\(_2\) pressure)
- evaluate the achievement of operating conditions
- start increase turbomachine operational speed
- evaluate achievement of self-propellant state
- transition turbomachine and its electric inverter from motor regime to generator regime
- capability of self-regulation
- control all parameters to be consistent with nominal operation parameters

It is necessary to verify the capacity and energy to start (battery, pressure tank) for a possible re-start.

| Operation range | Test the limit of the cycle for stable and safe operation of each component depending on the selected accident conditions |
| Shut down       | Tests of the system’s capability to interrupt (shut down) operation and its ability to get to a stand-by state, corresponding to the readiness to system restart must be conducted. |

The table focuses on the performance testing of the sCO\(_2\)-HeRo attached to the glass model. There is another table containing demonstration test running accident simulations. The content is will be influenced by the results of the performance test and is subject to be adjusted, if necessary.

### 3. SUMMARY AND OUTLOOK

The supercritical CO\(_2\) heat removal system is a very innovative reactor heat removal concept as it improves the safety of both currently operating and future BWRs and PWRs through a self-propellant, self-sustaining and self-launching, highly compact cooling system powered by an integrated Brayton-cycle using supercritical carbon dioxide (sCO\(_2\)) as its working fluid, called sCO\(_2\)-HeRo. A small-scale demonstrator is currently being built and attached to the PWR glass model at GFS, Essen, Germany. The demonstrator will be used for gaining operation experience of the heat removal system. Several operational transients and accident conditions will be simulated, the data will be used for validation of codes, in this project ATHLET.

It is planned to evaluate the feasibility of sCO\(_2\)-HeRo and perform test calculation with the ATHLET code. As a next step (beyond the scope of this project), these data will have to be validated on relevant scale and relevant environment (TRL-5 to TRL6).

### ACKNOWLEDGMENTS

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