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EXPERIMENTAL INVESTIGATION ON THE HEAT TRANSFER BETWEEN
CONDENSING STEAM AND S\textsuperscript{CO2} IN A COMPACT HEAT EXCHANGER

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ABSTRACT

In the frame of the “sCO2-HeRo” project (supercritical carbon-dioxide heat removal system) a self-launching and self-sustaining decay heat removal system for retrofitting into nuclear power plants is investigated. The system should be able to transfer the decay heat from the reactor core to the ultimate heat sink, e.g. the ambient air, in case of a station-blackout and loss-of-ultimate-heat-sink accident scenario. The system, in fact a Brayton cycle, consists of a compressor, a compact heat exchanger, a turbine, a sink heat exchanger and a generator. Since the turbine of the cycle produces more power than it is used in the compressor, the system is self-sustaining and excess electricity of the generator can be used e.g. for auxiliary devices in the power plant or for recharging batteries. Due to its convenient fluid properties near the critical point, for instance the heat capacity and the fluid density, supercritical carbon dioxide is used as working fluid.

Within the project a two-scale approach is applied. This means, that in the first part of the project a small-scale demonstrator unit of the sCO2-HeRo system is designed, manufactured and retrofitted into the pressurized water reactor glass model at Gesellschaft für Simulatorschulung (GfS), Essen. In the second part the received experimental results at the demonstrator will be used for validation of models e.g. for heat transfer and pressure drop. Afterwards, they will be transferred to component models on power plant size to be implemented into the thermal-hydraulic code ATHLET.

The Institute of Nuclear Technology and Energy Systems (IKE), University of Stuttgart, is responsible for the experimental investigation on the heat transfer between condensing steam and supercritical carbon-dioxide in the compact heat exchanger. Thereby, low pressure (glass model application) and high pressure (power plant application) investigations on the heat transfer between condensing steam and supercritical carbon-dioxide were carried out. This paper starts with an overview of the sCO2-HeRo system, retrofitted into a PWR, followed by a description of the investigated two-plate CHX test configuration. Afterwards, the test facility for the high pressure steam experiments is shown and the measurement parameter as well as the position of each measurement device is described. The analyzed experimental results, for example the sCO\textsubscript{2} pressure drop as a function of the sCO\textsubscript{2} mass flow rate, the heat transfer ratio between the steam side and the sCO\textsubscript{2} side or the surface temperature distribution on the sCO\textsubscript{2} side of the CHX, and the calculated measurement errors are discussed. Finally, the received results are summarized and a conclusion is given.

INTRODUCTION

In case of a station-blackout (SBO) and loss-of-ultimate-heat-sink (LUHS) accident scenario in a light water reactor, plant accident measures depend on the availability of external power. If this is not guaranteed, the core will be violated if no other cooling measures will be successful. Such scenarios lead to the development of self-launching, self-propelling and self-sustaining decay heat removal systems which are independent from external energy, but fulfilling the safety function transferring the decay heat from the reactor core to an ultimate heat sink, e.g. the ambient air. The supercritical carbon-dioxide (sCO\textsubscript{2}) heat removal system “sCO2-HeRo” is
such a system. It is a Brayton cycle, using sCO₂ as working fluid due to his convenient fluid properties near the critical point. The main components of the cycle are a turbo-compressor-system (TCS) with integrated generator, a compact heat exchanger (CHX) and an air-cooled heat exchanger. Since the turbine of the cycle produces more power than it is used for the compression work, excess electricity can be generated in the generator for any kind of auxiliary devices. Supercritical CO₂ is chosen as working fluid because it is not toxic, not combustible and abundantly available. Furthermore, the convenient fluid properties near the critical point, e.g. the fluid density and the specific heat capacity, allows the design of compact components. This is especially important for the compact heat exchanger, connecting the steam generator of the power plant with the sCO₂-HeRo cycle, because of space limitations in the containment.

Venker et al. [1-6] have studied the feasibility of such a decay heat removal system using the German thermal-hydraulic code ATHLET “Analysis of Thermal-hydraulic of Leaks and Transients” for a boiling water reactor (BWR). The simulation results have shown that the sCO₂-HeRo system has the potential to enlarge the grace time for interaction to more than 72 h. However, the results are based upon the implemented heat transfer and pressure drop models in ATHLET and these must be validated for the working fluid sCO₂.

Therefore, partners from three European countries are working in the first part of sCO₂-HeRo project on the design, manufacturing and assessment of a small-scale demonstrator unit into the pressure water reactor (PWR) glass model at Gesellschaft für Simulatorschulung (GfS), Essen, Germany. This is the step towards technology readiness level 3 (TRL3) [7]. By means of the small-scale demonstrator unit, experiments will be carried out and the received results will be used for validation of heat transfer and pressure drop correlations. In the second part the results will be transferred to component models on power plant scale to be implemented into the German thermal-hydraulic code ATHLET.

In the early stage of the project thermodynamic cycle calculations were performed for the small-scale demonstrator unit and for the power plant system. The optimum cycle parameters were determined with respect to maximum generator excess electricity. The received results as well as the determined optimum cycle parameters for the small-scale demonstrator unit of the glass model are summarized by Straetz et al. [8] and for the power plant scale by Hajek [9].

A scheme of the sCO₂-HeRo setup, attached to the steam generator of a pressure water reactor, is shown in Figure 1.

**Figure 1:** sCO₂-HeRo retrofitted into a PWR

In case of a combined SBO and LUHS accident scenario in the PWR power plant the main coolant pumps as well as the turbine are switched off, solenoid valve 1 is closed and solenoid valve 2 is opened automatically, establishing a natural circulation driven cooling loop in the primary loop. The decay heat power in the reactor core generates steam in the secondary circuit of the steam generator with a pressure of about 70 bar and a corresponding saturated steam temperature of about 286 °C. Driven by natural convection the steam flows into a compact heat exchanger (CHX), located above the steam generator, where the heat is transferred to the sCO₂ and the steam is condensed. The condensate flows downwards driven by gravity and re-enters the steam generator through the liquid line. The transferred condensing power of the steam is heating up the sCO₂ on the secondary side of the CHX (2-3), located in the containment. After heating up the sCO₂ it enters the turbine in the reactor building where it is expanded (3-4) followed by cooling down in an ultimate heat sink (4-1) to a defined temperature. Air-fans are intended to improve the heat transfer between the gas-coolers and the ultimate heat sink, the ambient air. If the turbine (3-4) of the sCO₂-HeRo system produces more power than it is used in the compressor (1-2), the system is self-sustaining and the generated excess electricity at the generator can be used for the air-fans.

**TWO-PLATE CHX TEST CONFIGURATION**

The experimental investigations on the heat transfer between condensing steam and sCO₂ are carried out with a two-plate CHX. The manufactured plates as well as a technical drawing are depicted in Figure 2 and Figure 3 and described.
A rectangular channel dimension with a width of 2 mm and a height of 1 mm (2x1 mm) is used on both sides (sCO\(_2\) Plate and H\(_2\)O Plate) of the two-plate CHX. This dimension was chosen with respect to recommendations for CHX’s from the literature, e.g. according to Hesselgreaves [13]. The design of the plates was determined after the selection of the channel dimension with respect to boundary conditions like the pressure, temperature, mass flow rate as well as from restrictions of the diffusion bonding machine.

The manufactured sCO\(_2\) plate with 15 straight rectangular channels and a channel length of 150 mm is shown on the left hand side of Figure 2. The technical drawing of the sCO\(_2\) plate is depicted in the upper picture in Figure 3. The wall thickness between two channels was determined according to the Barlow’s formula to 1.4 mm, which was additionally verified by a finite-element-method simulation with the software COMSOL to ensure that the CHX will be able to withstand all operation conditions. The plate thickness was determined conservatively to 5 mm. During operation the sCO\(_2\) enters the CHX plate at the bottom through a \(\frac{1}{2}\)“ pipe connection, flows upwards into the channels and is heated. Afterwards it leaves the CHX at the top through a second \(\frac{1}{2}\)“ pipe connection. Both plenums have a length of 49.6 mm, a width of 13 mm and a height of 1 mm (Figure 3). The second picture shows the H\(_2\)O plate with 15 straight channels, a channel length of 150 mm and a plate thickness of 2.4 mm. The steam inlet plenum is shown at the top and the outlet plenum at the bottom. Both have a length of 49.6 mm, a width of 13 mm and a height of 1 mm. The steam cover plate has a plate thickness of 4 mm and is depicted in the third picture in Figure 2. Two drillings with a diameter of 13 mm are included in the plate, the upper one for the steam inlet and one for the outlet of the condensate at the bottom. The last picture shows the diffusion bonded two-plate CHX with 2x1 mm channels. After welding the pipe connections onto the CHX, it will be ready for the installation into the test section.

**TEST FACILITIES**

Within the sCO\(_2\)-HeRo project IKE, University of Stuttgart (USTUTT) is responsible for the experimental investigation on the heat transfer between condensing steam and sCO\(_2\) in the CHX. During the project, low-pressure and high-pressure steam experiments are carried. They correspond to the small-scale demonstrator unit for the glass model and for power plant application. The investigations for the power plant application take place in the laboratory of IKE using two test facilities. The first one is the SCARLETT test loop which provides sCO\(_2\) under defined conditions and the second one is the steam cycle which provides high-pressure steam. The piping and instrumentation (P&I) diagram of the SCARLETT test loop [10] is depicted in Figure 4.
At the start the pressure vessels (1, 9) are filled with CO₂ by a gas bottle after evacuating the loop with a vacuum pump. During operation, liquid CO₂ flows from the pressure vessel 1 into an electrical heated evaporator (2) where it is slightly superheated. In a demister unit (3) remaining liquid CO₂ is separated from the flow before it enters a compressor (4) where it is compressed to a defined pressure and simultaneously compression-heated. After the compressor the sCO₂ is conditioned before it enters the test section, which means that a defined temperature can be adjusted via heating or cooling the sCO₂ mass flow rate. In a test-section (red box) different kind of experiments can be performed, e.g. the heat transfer in CHX with condensing steam and sCO₂ or electrically heated plates. The installed measurement devices, for instance resistance thermometers (Pt-100), pressure gauges and mass flow meters, at the inlet (5) and outlet (5’) of the test section measures relevant parameters of the experiments. The sCO₂ is cooled down in a gas chiller (6) after leaving the test section and before entering an expansion valve (7). In a condenser (8) the CO₂ can be cooled down again before it flows into the pressure vessel 2 (9). From there it is pumped back into vessel 1.

The sCO₂ mass flow rate $\dot{m}_{sCO₂}$ can be varied in the SCARLETT test loop 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 P&I diagram of the high-pressure steam cycle is depicted in Figure 5 and described as follows.

![Figure 5: P&I diagram of the high-pressure steam cycle](image)

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 were determined under consideration of the carried out low-pressure steam cycle (0.3 bar) experiments for the glass model application [14]. According to the low-pressure experiments, six measurement campaigns were carried out.
campaigns were carried out in which different inlet conditions on both sides (H₂O and sCO₂) of the two-plate CHX were used to obtain 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 [11] and from internal restrictions at the test facilities. To be able to compare the results of both, the low-pressure and high-pressure steam cycle, the same measurement campaigns were used (Table 1).

In the DP experiments according to campaign 1, 2 and 3 the sCO₂ mass flow rates $\dot{m}_{\text{sCO}_2}$ from 46 g/s to 68 g/s correspond to the water volume flow rates $\dot{m}_{\text{H}_2\text{O}}$ 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 done. Therefore, a constant sCO₂ mass flow rate $\dot{m}_{\text{sCO}_2}$ of 37 g/s and gradually increasing water volume flow rates $\dot{m}_{\text{H}_2\text{O}}$ 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, new 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.

For monitoring the temperatures on the surface of the CHX during the investigation, nine resistance thermometers (Pt-100) are mounted on the sCO₂ plate. The position of each Pt-100 is shown in the CAD drawing (Figure 6).

The results show, that an increased sCO₂ mass flow rate $\dot{m}_{\text{sCO}_2}$ leads to an increased pressure drop $\Delta P_{05}$, for a constant inlet pressure P₀₄ and inlet temperature T₀₆. For example, that is shown by the 100 bar results, where a sCO₂ mass flow rate $\dot{m}_{\text{sCO}_2} = 45$ g/s leads to a sCO₂ pressure drop $\Delta P_{05} = 0.17$ bar, 55 g/s leads to 0.26 bar and 67 g/s leads to 0.37 bar. The results additionally show that an increased inlet pressure P₀₄ leads to decreased sCO₂ pressure drops $\Delta P_{05}$ - for a constant mass flow rate $\dot{m}_{\text{sCO}_2}$ and inlet temperature T₀₆. This can be explained by the equation of continuity and the fluid density. The fluid density of sCO₂ depends on the pressure and the lower the pressure, the closer the pressure is to the critical point, the lower is the density and due to that the higher is the pressure drop for a given sCO₂ mass flow rate because of higher flow velocities in the channels. According to the results depicted in Figure 7 a sCO₂ inlet pressure P₀₄ = 95 bar, combined with an inlet temperature T₀₆ = 40 °C and a mass flow rate $\dot{m}_{\text{sCO}_2} = 56$ g/s, leads to a pressure drop $\Delta P_{05} = 0.27$ bar, P₀₄ = 100 bar leads to $\Delta P_{05} = 0.26$ bar and P₀₄ = 110 bar leads to $\Delta P_{05} = 0.24$ bar.

The results of the heat input into the sCO₂ $Q_{\text{sCO}_2}$ are depicted in Figure 8 as a function of the condensing power of the steam $Q_{\text{H}_2\text{O}}$ for the ODP experiments (Table 1). $Q_{\text{H}_2\text{O}}$ and

![Figure 7: Results of $\Delta P_{05}$ and $\dot{m}_{\text{sCO}_2}$ - DP](image-url)

The experimental results of the sCO₂ pressure drop $\Delta P_{05}$ in the two-plate CHX with 15 straight channels and a channel dimension of 2x1 mm is shown in Figure 7 for the DP experiments as a function of the sCO₂ mass flow rate $\dot{m}_{\text{sCO}_2}$.

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Q_{\text{CO}_2} were calculated in general according to Eq. 1, using the measured mass flow rates \( \dot{m} \) and the enthalpy differences between the inlet \( h_{\text{in}} \) and outlet \( h_{\text{out}} \) of the fluids at the two-plate CHX. The enthalpies were calculated with NIST REFPROP, using the measured fluid temperatures and pressures.

\[
Q = \dot{m} \cdot (h_{\text{in}} - h_{\text{out}})
\]  

(1)

Figure 8: Results of Q_{\text{CO}_2} and Q_{\text{H}_2\text{O}} - ODP

The received results of the 100 bar experiments (Figure 8) are described as example in more detail. A calculated condensing power of the steam \( Q_{\text{H}_2\text{O}} \) = 458 W leads to a calculated sCO\(_2\) heat input \( Q_{\text{sCO}_2} \) = 395 W, \( Q_{\text{H}_2\text{O}} \) = 708 W leads to \( Q_{\text{sCO}_2} \) = 607 W and \( Q_{\text{H}_2\text{O}} \) = 1267 W leads to \( Q_{\text{sCO}_2} \) = 1179 W. Furthermore it can be seen, that on the one hand side the graphs have a similar tendency for all investigated inlet pressures \( P_0 \), and on the other hand side that there is a schematically offset between the condensing power of the steam \( Q_{\text{H}_2\text{O}} \) and the sCO\(_2\) heat input \( Q_{\text{sCO}_2} \). This offset can be explained by thermal losses in the test section due to high temperatures of about 290 °C. Taken into account the results, the offset \( Q_{\text{H}_2\text{O \ offset}} \) can be calculated by the energy balance according to Eq. 2:

\[
Q_{\text{H}_2\text{O \ offset}} = Q_{\text{H}_2\text{O}} - Q_{\text{sCO}_2}
\]  

(2)

Figure 9: Results of T07-T06 and Q_{\text{CO}_2} - ODP

The calculated results of the sCO\(_2\) temperature increase T07-T06 were summarized in Figure 9 as a function of the sCO\(_2\) heat input \( Q_{\text{CO}_2} \) for the ODP measurement campaigns 4, 5 and 6.

The results of the 110 bar measurement campaign are described in more detail at the beginning. A sCO\(_2\) heat input \( Q_{\text{CO}_2} \) = 379 W leads to a sCO\(_2\) temperature increase T07-T06 = 2.4 °C, \( Q_{\text{CO}_2} \) = 600 W leads to T07-T06 = 3.7 °C, \( Q_{\text{CO}_2} \) = 756 W leads to T07-T06 = 4.6 °C and \( Q_{\text{CO}_2} \) = 1139 W leads to T07-T06 = 6.5 °C. In addition, the other results depicted in Figure 9 have a similar linear tendency only with different gradients because of different specific heat capacities. Moreover, a lower inlet pressure P04 leads to lower sCO\(_2\) temperature increases T07-T06 because of higher specific heat capacities near the critical point. A sCO\(_2\) heat input \( Q_{\text{CO}_2} \) = 1150 W, combined with a sCO\(_2\) mass flow rate \( \dot{m}_{\text{CO}_2} \) = 37 g/s and a sCO\(_2\) inlet temperature T06 = 40 °C, leads to a sCO\(_2\) temperature increase T07-T06 = 6.5 °C for P04 = 110 bar, to T07-T06 = 4.7 °C for P04 = 100 bar and T07-T06 = 3.6 °C for P04 = 95 bar. The specific heat capacity \( c_p \) can be calculated in general for each measurement parameter according to Eq. 3:

\[
c_p = \frac{Q_{\text{CO}_2}}{\dot{m}_{\text{CO}_2} \cdot (T07 - T06)}
\]  

(3)

with the sCO\(_2\) heat input \( Q_{\text{CO}_2} \), the sCO\(_2\) mass flow rate \( \dot{m}_{\text{CO}_2} \) and the sCO\(_2\) temperature increase T07-T06. For the 110 bar measurement campaign (Figure 9) the specific heat capacity \( c_p \) is in the range of 4.3 kJ/kg K to 4.8 kJ/kg K, for the 100 bar campaign from 6.1 kJ/kg K to 6.9 kJ/kg K and for the 95 bar campaign between 7.9 kJ/kg K and 8.8 kJ/kg K.

The experimental results of the surface temperatures T on the sCO\(_2\) side of the CHX are depicted in Figure 10 as a function of the position X of the Pt-100 (Figure 6). The results are received from the ODP measurement campaign 4 with a
sCO₂ heat input of $Q_{sCO₂} = 755$ W, an inlet temperature $T_{06} = 40$ °C and a sCO₂ mass flow rate $\dot{m}_{sCO₂} = 37$ g/s.

Figure 10: Results of $T$ and $X$ - ODP and $Q_{sCO₂} = 755$ W

The depicted results of the surface temperatures have a symmetrical profile with lower temperatures in the center and higher temperatures at the outer area of the two-plate CHX, which can be explained by inhomogeneous mass flow distributions over all channels. As example, the temperature profile at level 3 shows, that the temperatures $T_{07} = 42.0$ °C (left hand side) and $T_{09} = 41.8$ °C (right hand side) are similar. The temperature $T_{08} = 41.3$ °C in the central axis of the CHX is about 0.5 °C lower than $T_{07}$ and $T_{09}$. The gradually increasing surface temperatures from level 1 to level 3 are described in the following at position $X = 0$ mm. The sCO₂ enters the CHX with a temperature of 40 °C and flows upwards into the channels. Level 1 is located 30 mm above the plenum and the measured surface temperature is $T_{02} = 39.0$ °C. Flowing upward, the sCO₂ is heated in the CHX due to the heat transfer of condensing steam. This leads to a surface temperature of $T_{05} = 39.4$ °C on level 2 and $T_{08} = 41.3$ °C on level 3. In addition, the measured surface temperatures correspond to the results of the sCO₂ temperature increases $T_{07}$-$T_{06}$ according to Figure 9. There, a sCO₂ mass flow rate $\dot{m}_{sCO₂} = 37$ g/s, an inlet pressure $P_{04} = 110$ bar, an inlet temperature $T_{06} = 40$ °C and a heat input $Q_{sCO₂} = 755$ W leads to a temperature increase of about $T_{07}$-$T_{06} = 4.5$ °C - which corresponds to the measured surface temperatures on level 3 of about 42.0 °C. But it should be mentioned, that the received surface temperatures are always lower than the sCO₂ fluid temperatures $T_{07}$ at the outlet of the CHX due to thermal losses and the measurement position of level 3, which is 30 mm below the sCO₂ outlet.

Finally, the experimental results of the surface temperatures $T$ on the sCO₂ side of the CHX are shown in Figure 11 as a function of the position $X$ of the Pt-100. The results correspond to the ODP measurement campaign 4 with an sCO₂ heat input of $Q_{sCO₂} = 1140$ W.

Figure 11: Results of $T$ and $X$ - ODP and $Q_{sCO₂} = 1140$ W

The shown results in Figure 11 have similar symmetrical tendencies, compared to the depicted results in Figure 10. As example, the increase of the surface temperature at position $X = 0$ mm is described in more detail. A sCO₂ mass flow rate $\dot{m}_{sCO₂} = 37$ g/s, a sCO₂ inlet pressure $P_{04} = 110$ bar and a sCO₂ inlet temperature $T_{06} = 40$ °C leads to a surface temperature of $T_{02} = 39.0$ °C on level 1. Flowing upward, the sCO₂ is heated in the CHX due to the heat transfer of condensing steam, which leads to a surface temperature of $T_{05} = 40.1$ °C on level 2 and $T_{08} = 44.1$ °C on level 3. Comparing the results of both campaigns (Figure 10 and Figure 11) they show, that the surface temperatures on level 1 are quite similar with a temperature of about $T_{02} = 39.2$ °C. On level 2 there is a discrepancy of 0.7 °C between the surface temperature $T_{05} = 39.4$ °C (755 W) and the surface temperature $T_{05} = 40.1$ °C (1140 W). On level 3 there is a discrepancy of 2.8 °C between the surface temperature $T_{05} = 41.3$ °C (755 W) and the surface temperature $T_{05} = 44.1$ °C (1140 W). The temperature discrepancies on level 2 and especially on level 3 can be explained by the way of the heat input into the sCO₂ from the condensing power of the steam $Q_{H2O}$. A higher heat input $Q_{sCO₂}$ into the sCO₂ corresponds to a higher steam condensing power $Q_{H2O}$ and this lead to increased steam mass flow rates. Increased steam mass flow rates need more heat transfer area and this leads to a forced steam mass flow downwards the CHX in the direction of level 3 and level 2.

The error bars, shown in Figure 7 - Figure 11, were derived from manufacturer’s instructions and from calculated measurement error propagations.

The temperature measurement uncertainty of a Pt-100 is given as a function of the measured temperature $T$ according to $+/- (0.15°C+0.002*T)$. The pressure measurement uncertainty depends on the pressure measurement type and on the
measurement range. The sCO₂ inlet pressure P04 into the CHX was measured with an uncertainty of +/- (0.5%*200bar) and the sCO₂ pressure drop P05 with an error of +/- (0.15%*10bar). The sCO₂ mass flow rate \(m_{sCO₂}\) was measured with an accuracy of +/- 0.8 g/s. The water volume flow rate \(m_{H2O}\) on the steam side has an uncertainty of +/- (5%*\(m_{H2O}\)) and the \(H_2O\) inlet and outlet pressures P02 and P03 were measured with an accuracy of +/- (0.5%*100bar).

The error propagations for the calculated enthalpies \(\sigma_h\) and for the calculated sCO₂ heat input \(\sigma_{Q_{sCO₂}}\) as well as steam condensing power \(\sigma_{Q_{H2O}}\) are described more in detail. Eq. 4 shows the equation for the statistical error propagation

\[
\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \ldots} \tag{4}
\]

with \(\sigma_1\): measurement uncertainty of the first independent parameter and \(\sigma_2\): measurement uncertainty of the second independent parameter, which implies the uncertainties to be not correlated.

For the calculation of the sCO₂ enthalpy uncertainty at the inlet of the CHX \(\sigma_{sCO₂-in}\) (Eq. 5) four enthalpies were used. The first one was \(h_{sCO₂-in}|T06/P04_{max}\), which was a function of the measured sCO₂ inlet temperature T06 and the maximum possible inlet pressure P04\(_{max}\) according to pressure measurement uncertainties. The second one was \(h_{sCO₂-in}|P04/T06_{min}\), which was calculated with the measured sCO₂ inlet temperature T06 and the minimum possible inlet pressure P04\(_{min}\). The third one was \(h_{sCO₂-in}|P04/T06_{max}\), which was a function of the measured sCO₂ inlet pressure P04 and the maximum possible inlet temperature T06\(_{max}\). The fourth one was \(h_{sCO₂-in}|P04/T06_{min}\), which was calculated with the measured sCO₂ inlet pressure P04 and the minimum possible inlet temperature T06\(_{min}\). The propagated sCO₂ enthalpy uncertainty at the outlet of the CHX \(\sigma_{sCO₂-out}\) was calculated in the same way as for \(\sigma_{h_{sCO₂-in}}\), only with the sCO₂ outlet temperature T07 and sCO₂ outlet pressure \(p_{sCO₂-out}\).

\[
\sigma_{h_{sCO₂-in}} = \sqrt{\frac{(h_{sCO₂-in}|T06/P04_{max} - h_{sCO₂-in}|T06/P04_{min})^2 + (h_{sCO₂-in}|P04/T06_{max} - h_{sCO₂-in}|P04/T06_{min})^2}{2}} \tag{5}
\]

The heat input into the sCO₂ was calculated according to \(Q_{sCO₂} = m_{sCO₂} * (h_{sCO₂-in} - h_{sCO₂-out})\). It can be seen, that \(Q_{sCO₂}\) is a function of three independent parameters. According to the linearized Taylor-series and the propagation of uncertainty, for independent parameters, the error propagation \(\sigma_{Q_{sCO₂}}\) was calculated after rewriting according to Eq. 6:

\[
\sigma_{Q_{sCO₂}} = \sqrt{(m_{sCO₂} * (\sigma_{h_{sCO₂-in}})^2 + (m_{sCO₂} * (\sigma_{h_{sCO₂-out}} - \sigma_{h_{sCO₂-in}}))^2 + (\sigma_{m_{sCO₂}})^2 + (\sigma_{h_{sCO₂-out}})^2 + (\sigma_{h_{sCO₂-in}})^2)} \tag{6}
\]

The error propagation \(\sigma_{Q_{sCO₂}}\) includes the calculated sCO₂ enthalpies at the inlet \(h_{sCO₂-in}\) and outlet \(h_{sCO₂-out}\) of the CHX, the measurement error of the sCO₂ mass flow rate \(\sigma_{m_{sCO₂}}\) = +/- (0.8 g/s), the measurement results of the sCO₂ mass flow rate \(m_{sCO₂}\) and the calculated enthalpy uncertainties \(\sigma_{h_{sCO₂-out}}\) and \(\sigma_{h_{sCO₂-in}}\). The error propagation was repeated in the same way for the steam side.

The results have shown an error propagation of less than 6% for the calculated measurements values for the sCO₂ heat input \(Q_{sCO₂}\) and the steam condensing power \(Q_{H2O}\).

**CONCLUSION**

An advanced heat removal system, a Brayton cycle with supercritical sCO₂ as working fluid, is currently investigated within the EU-funded sCO2-HeRo project. The system consists of a turbine, a compressor, a generator, a compact heat exchanger, gas-coolers and auxiliary devices. In the design point of the system it is assumed, that the turbine provides more power than it is used for the compression work, which leads to a self-launching, self-propelling and self-sustaining decay heat removal system. In the EU-funded project a two-scale approach is applied. Showing the feasibility in the first part of the project a small-scale demonstrator unit of the sCO2-HeRo system is designed, manufactured and attached into the PWR glass model at GfS, Essen. In the second part the received experimental results at the demonstrator will be used for validation of models e.g. for heat transfer and pressure drop. Afterwards, they will be transferred to component models on power plant size to be implemented into the German code ATHLET.

The Institute of Nuclear Technology and Energy Systems (IKE) is responsible for the investigation of the compact heat exchanger, which connects the steam side of the power plant with the sCO₂ side of the sCO2-HeRo system. Using two test facilities, the sCO₂ SCARLETT test loop and the high-pressure steam cycle, experimental investigations on the heat transfer between condensing steam (70 bar, 286 °C) and sCO₂ were performed in the CHX with 15 straight rectangular channels, a channel length of 150 mm an a channel dimension of 2x1 mm.

The results of the sCO₂ pressure drop \(\Delta P05\) in the CHX show a typical parabolic profile with an increasing pressure drop for increasing sCO₂ mass flow rates. The depicted results of the heat input \(Q_{sCO₂}\) into the sCO₂ 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. The sCO₂ temperature increase T07-T06 shows for all measurement campaigns a nearly linear profile, which can be explained by the specific heat capacity. Additionally, the plate surface temperatures were measured during the measurement campaigns on the sCO₂ side of the CHX with nine Pt-100. The results show lower plate surface temperatures T in the center axis of the CHX and higher temperatures at the outer area, which can be explained by inhomogeneous mass flow distributions over all channels.

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NOMENCLATURE

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<td>$h$</td>
<td>Enthalpy</td>
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<td>$\dot{m}$</td>
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<td>$Q$</td>
<td>Heat Power</td>
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<td>$R$</td>
<td>Heat Transfer Ratio</td>
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<td>Temperature</td>
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<tr>
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<td>$\sigma$</td>
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<tr>
<td>$sCO2$</td>
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ABBREVIATIONS

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<td>GfS</td>
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<td>HeRo</td>
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<td>IKE</td>
<td>Institute of Nuclear Technology and Energy Systems</td>
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<td>LUHS</td>
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<td>P&amp;I</td>
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REFERENCES


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