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Concept and Preliminary Design of a 600°C+ sCO\textsubscript{2} Test Facility

2\textsuperscript{nd} European sCO\textsubscript{2} Conference, August 30-31 2018, Essen Germany
Content

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- Motivation for sCO₂ power cycles
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Component design aspects
- Heater
- Cooling system
- Recirculation blower

Summary

Source: Gampe, Spura (2016), TU Dresden
Motivation for sCO$_2$ power cycles

**Important advantages:**

- **Reduction in size and complexity** compared to steam driven cycles
- **Higher possible efficiencies** especially in low temperature applications

**Fig. a):** Comparison of the exergetic efficiency of a heat recovery steam generator sCO$_2$ vs. water based steam

![Graph showing exergetic efficiency comparison](image)

**Fig. b):** Size comparison of a 10 MW turbine for usage with water based steam / sCO$_2$

![Size comparison diagram](image)
Project overview
Target Applications

CARBOSOLA Project:
Setting up a MW\textsubscript{t} class sCO\textsubscript{2} test facility which targets development of WHR and CSP applications:

Technology development
- Component development and testing
- Static and transient system analysis
- Process reliability and -safety

Generic Investigations
- Fluid composition / impact on cycle performance
- Validation of CFD models
- Heat transfer modelling
- Near critical point stability criteria
- Failure modes and effect analysis (FMEA)

Target parameters:
\[
T = 600+{\degree}C, \ p = 300 \ \text{bar}, \ Q_{\text{th}} = 2.5 \ \text{MW}
\]
Project overview
Classification in relation to other sCO\(_2\) test rigs

Component & Large System Testing

Small Scale Component & System Integrity Tests

Fundamental research

HZDR / TU Dresden sCO\(_2\) Test-Facility, DE
\(Q_{th} = 2.5\) MW
\(T = 600^\circ\)C @ 300 bar

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<th>Temperature [(^\circ)C]</th>
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J. Moore, Commissioning of a 1 Mwe Supercritical CO\(_2\) Test Loop, 8th Int. sCO\(_2\) Symposium 2018

A. Kruizenga, Supercritical CO\(_2\) Heat Exchanger Fouling, 6th Int. sCO\(_2\) Symposium 2016
Rig concept
Loop definition and basic architecture

Stepwise implementation of three expansion stages:

- **Stage 1:** Basic cycle with test section for simple fluid circulation

- **Stage 2:** Addition of devices for recuperator testing

- **Stage 3:** Installation of compressor and turbine to complete the cycle

Site of installation is chosen to be at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) using the on-site existing infrastructure

**Current status:** Preliminary design of stage 1

**Fig. a):** Basic test loop scheme (later expansion stages marked blue)
Rig concept
Basic design aspects

Detailed rework of the basic scheme including a instrumentation draft

First boundary conditions for component design:

- Selection of suitable Materials for the HT parts based on literature data:
  - 347HFG as potential alternative for expensive Ni-Alloys

- Selection of appropriate pipe diameters
  - Comparative study on different nominal diameters
  - DN60 chosen as preferred diameter uniformly for all interconnecting pipes

Fig. a): Basic Instrumentation of first expansion stage
Component design aspects
Heater design – Basic concept

Heating should be done **electric** on base of on-site available infrastructure

**Design objectives:**

- Staged setup split up in two modules 2.25 MW (step-wise control) and 0.25 MW (infinitely variable)
- Scalability regarding later extensions
- Cost-oriented stainless steel based solution

![Block diagram of the basic heater concept](image-url)

\[ CO_2, \quad \dot{m} = 3.5 \text{ kg/s} \]

\[ p_2 = 300 \text{ bar} \]

\[ \theta_2 = 100 \text{ °C} \]

\[ p_{32} = 300 \text{ bar} \]

\[ \theta_{32} = 550 \text{ °C} \]

\[ p_3 = 300 \text{ bar} \]

\[ \theta_3 = 600 \text{ °C} \]

\[ \approx 2.25 \text{ MW} \]

\[ \approx 0.25 \text{ MW} \]
Component design aspects
Heater design – First draft

Similar concept is already in use at HZDR for overheated steam

Split up of the CO₂ to several small pipes used as joule heating elements

First calculation approach:
- Usage of stainless steel leads to 3 modules with dimensions of 3m x 1.6m x 1m each
- Limiting factor is the allowable stress of the tube material
  → Significant reduction in size by using IN740 (reduction in height of approx. 50%, nr. of modules decreased from 3 to 2)

Next steps: detailed examinations, comparison with other heating concepts

Fig. a): First draft for the heater using SS 347HFG
Component design aspects
Cooler design – Basic concept

Integration in a **existing heat removal system** at HZDR

- Water-glycol mixture as secondary heat transfer media
- Heat rejection is done by a roof mounted heat exchanger to the ambient air ($\Delta T_{\text{min}} = 10$ K)
- Potentially high particle load due to oxidation of other attached test rigs using carbon steel for their exchangers

First design approach: **Shell & tube HX**

→ robust design, low risk for particle induced plugging. But: Large dimensions

Fig. a): Dimensioning result using the shell & tube architecture
Component design aspects
Cooler design – Comparison with PCHE

- Comparison with PCHE architecture shows significant reduction in size
- PCHE more applicable than the shell & tube solution
- Actually more work is needed concerning particle induced channel plugging

Fig. a): Dimensioning result using the printed circuit architecture
Fig. b): Size comparison of both HX architectures related to the present application
Component design aspects
Recirculation blower design – Basic concept

**Objective:** Compensation of occurring pressure losses to ensure a reliable fluid circulation

Conservative estimation of pressure losses including the test section: **15 bar**

**Design specifications:**

- \( T_{in} = 550 ^\circ C \) (design for HT-circulation)
- \( \pi = 1.05 \) (285 to 300 bar)
- \( m = 3.5 \) kg/s

→ **radial type impeller** based on cordier diagram

*Fig. a): First impeller draft based on 1D design calculations*
Component design aspects
Recirculation blower design – First numerical results

Impeller model related to the first draft as evaluation base for numerical studies

Challenge:
• Fluid circulation should be possible for variable temperature levels

→ Sufficient functionality for varying inlet temperatures needed

Numerical analysis for the design point corresponding to 1D predesign

Further investigations are currently ongoing

Fig. a): Impeller example, $d_s=37\text{mm}$, $d_2=80\text{mm}$
Fig. b): Meridional pressure contour at the design point
Summary

CARBOSOLA Project: Implementation of an megawatt class sCO$_2$ test facility which addresses technology development and generic investigations for WHR and CSP applications

Status:

- Detailed concept including instrumentation aspects is finally available
- Basic boundary conditions are almost set including material selection and appropriate pipe diameters
- Conceptual work on selected components for design and integration in the on-site available infrastructure

Next Steps:

- Continuation of the design process
- Detailed engineering including numerical investigations
- Commissioning
Thank you for listening.