First Operational Experience From The Supercritical CO2 Experimental Loop

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CVR projects

- **GoFastR (Gas cooled Fast Reactor) / FP7 / 2010-2013**
  - Partners: AMEC, Areva, KIT, Rolls-Royce, CVR ……
  - Optimisation of sCO2 cycle for GFR reactor

- **SUSEN (Sustainable Energy) / 2012 – 2017 / sCO2 loop built**
  - Design, construction, calculations, fabrication, commissioning
  - First tests finished (TG, HXs)

- **sCO2-HeRo (sCO2 Heat Removal system) / H2020 / 2015 – 2018**
  - Partners – UDE, USTUTT, GfS, TUD, CVR, UJV,
  - Goals – sCO2 safety system for present NPP, micro-scale demonstration unite

- **Internal project / 2017 – 2018 / Design of Fluoride salt cooled High temperature Reactor - potential applications for small modular reactors with sCO2 conversion cycle**

- **sCO2-Flex / H2020 / 2018 – 2020 / ongoing**
  - Partners – EDF, GE, FivesCryo, USTUTT, UDE, POLIMI, CVR, UJV, CSM, ZABALA
  - Goals – design of 25MWe sCO2 cycle powered by coal fired boiler
    - Cycle calculations (EDF, POLIMI, CVR)
    - T-H code validation and benchmarking (CVR, POLIMI)
    - HX testing (FivesCryo, USTUTT, CVR)
    - Corrosion tests (CVR, CSM)
    - Compressor testing (full scale) (GE, UDE)
    - Turbine design (GE, UDE)
    - Boiler design (UJV)
The sCO2 experimental loop was constructed within SUSEN (Sustainable Energy) project in 2017.

Providing a facility to study key aspects of the sCO2 Brayton cycle (heat transfer, system dynamics, component characteristics, corrosion, erosion etc.) with wide range of parameters: temperature up to 550°C, pressure up to 30 MPa.

The sCO2 loop is flexible, easy to modify and suitable for testing key components of the Brayton cycle:

- compressor and turbine
- heat exchangers
- heaters
- valves
CVR sCO2 experimental loop description

The main operating parameters of the sCO2 primary loop

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum operation pressure</td>
<td>25 MPa</td>
</tr>
<tr>
<td>Maximum pressure</td>
<td>30 MPa</td>
</tr>
<tr>
<td>Maximum operation temperature</td>
<td>550°C</td>
</tr>
<tr>
<td>Maximum temperature in HTR</td>
<td>450°C</td>
</tr>
<tr>
<td>Maximum temperature in LTR</td>
<td>300°C</td>
</tr>
<tr>
<td>Nominal mass flow</td>
<td>0.35 kg/s</td>
</tr>
<tr>
<td>Total heating power</td>
<td>110 KW</td>
</tr>
</tbody>
</table>
Operational procedures with sCO2 loop

- **Start-up, normal operation, shut-down**
- **Vacuuming** - To eliminate all atmospheric gases and unwelcome moisture. The loop is equipped with several joints. Check if the loop is gas tight.
- **Filling** - a standard pressurized bottle (99.995) is introduced. The weight of the bottle is measured.
- **Circulation** - the main circulation pump can start circulating the CO$_2$ content around
- **Heating** - To adjust (increase) the pressure in the system the heaters are switched on
- **Pressure control**
  - air driven reciprocating compressor is used to boost the CO2 to the loop
  - reducing the pressure can be performed through opening the bleeding valves with orifices installed in the pipe
  - pressure relief valves
- **Flow rate control** - Main circulation pump speed drive
- **Temperature control** – heaters, coolers
- **The shut-down procedure** is performed through the heating power control.
## Applications in the CVR sCO2 loop – testing of air finned tube Sink HX

### Diagram Description
- **Containment**
- **SG**
- **Reactor**
- **MCR**
- **PSV**
- **PRV**
- **compact HX**
- **sink HX**
- **sCO2 turbomachinery**
- **Air fan**

### Variable Table

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{sCO2}$</td>
<td>7 – 10</td>
<td>MPa</td>
<td>Pressure – inlet of sCO2 in the sink HX – controlled</td>
</tr>
<tr>
<td>$T_{sCO2_in}$</td>
<td>50 – 166</td>
<td>°C</td>
<td>Temperature of sCO2 inlet to the sink HX – controlled</td>
</tr>
<tr>
<td>$T_{sCO2_out}$</td>
<td>25 – 37</td>
<td>°C</td>
<td>Temperature of sCO2 outlet from the sink HX – measured</td>
</tr>
<tr>
<td>$\dot{m}_{sCO2}$</td>
<td>0.1 – 0.32</td>
<td>kg/s</td>
<td>Mass flow rate of the sink HX – controlled</td>
</tr>
<tr>
<td>$T_{air_in}$</td>
<td>23 – 31</td>
<td>°C</td>
<td>Temperature of air inlet to the sink HX – *controlled</td>
</tr>
<tr>
<td>$T_{air_out}$</td>
<td>31 – 65</td>
<td>°C</td>
<td>Temperature of air outlet from the sink HX – measured</td>
</tr>
<tr>
<td>$V_{air_out}$</td>
<td>6 000 – 13 000</td>
<td>m³/h</td>
<td>Volumetric flow rate of air outlet from the sink HX – controlled</td>
</tr>
</tbody>
</table>
Sink HX - geometry

Length = 1.4 m, Width = 2.2 m
Number of tubes = 8
Number of rows in depths = 6
Tube Ø 12 mm x 0.7 mm
Number of passes = 5.5
Length of a tube = 46.2 m long (1.4 x 6 x 5.5 = 46.2 m)
The thickness of fin = 0.5 mm
pitch between the fins = 2.4 mm
The pitch $s_1=50$ mm, $s_2=25$ mm and $s_3=35$ mm.
Tube - SS 304, Fins - Al
Measurement data – thermal balance

- Thermal balance between the sCO2 and air side has been compared with +/-15% error.
Comparison of the measurement with correlations from the literature

**sCO2 – tube side**

Gnielinski

\[
Nu = \frac{\frac{\zeta}{8} \cdot \text{Re} \cdot \text{Pr}}{1 + 12.7 \cdot \sqrt{\frac{\zeta}{8} \left( \frac{1}{\text{Pr}^3} - 1 \right)}} \left[1 + \left( \frac{d}{L} \right)^{\frac{2}{3}} \right] \quad [-] \quad \frac{d}{L} \leq 1 \quad 0.1 \leq \text{Pr} \leq 1000
\]

\[\zeta = (1.8 \cdot \log(\text{Re}) - 1.5)^2 \quad [-]
\]

**Air – shell side**

Institute of Physics and Power Engineering, Moscow

\[
Nu = 0.192 \cdot \text{Re}^{0.65} \left( \frac{s_1}{s_2} \right)^{0.2} \cdot \left( \frac{h'}{d_{outer}} \right)^{-0.14} \cdot \left( \frac{u + \delta_{fin}}{d_{outer}} \right)^{0.18} \cdot \text{Pr}^{\frac{2}{3}} \cdot \left( \frac{\text{Pr}}{\text{Pr}_{fin}} \right)^{0.25} \quad [-] \quad \text{Re}_{d_{outer}} = 10^2 \div 2 \cdot 10^4
\]

VDI – Heat Atlas

\[
Nu = 0.38 \cdot \text{Re}^{0.6} \left( \frac{A_{outer}}{A_{tube}} \right)^{-0.15} \cdot \text{Pr}^{\frac{1}{3}} \quad [-] \quad \text{Re}_{d_{outer}} = 10^3 \div 10^5
\]

\[
\alpha_{outer} = \alpha_{ideal} \cdot \frac{A_{fin}}{A_{outer}} \left( \eta_{fin} + \frac{A_{tube - fin}}{A_{fin}} \right) \quad [W / m^2K]
\]

\[
k = \frac{1}{\frac{1}{\alpha_{outer}} + \frac{1}{A_{outer}} \cdot \left( \frac{1}{\alpha_{inner}} + \frac{\delta_{tube}}{\lambda_{tube}} \right)} \quad [W / m^2K]
\]
Implementation into the numerical model

- Modelica library – ClaRa (Clasius-Rankine cycles)
- Open source
- Dynamic investigation of power processes
The results of calculated averaged overall heat transfer coefficients using correlations (Gnielinski for sCO2 and IPPE or VDI for the air) and experimentally determined values show for the performed tests reasonably low error of +25 % and −10 %.
For a transient scenario – step-wise drop of \( \dot{m}_{sCO2} \) followed by loss of electric heating power, a Modelica code with newly implemented sink HX model was used. Simulation matches the measurement results quite well with minor mean deviations (\( \dot{m}_{sCO2} 5 \% \), \( V_{\text{air\_out}} \) 5 \%, \( T_{sCO2\_in} \) 2 \%, \( T_{sCO2\_out} \) 3 \%, \( p_{sCO2\_in} \) 3 \%, \( T_{\text{air\_out}} \) 3 \%).

Applications in the CVR sCO2 loop – performance test of TG

- UDE – design

- Achieved design speed
- Good agreement between CFD and test results

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle</td>
<td>Mass flow</td>
<td>0.65 kg/s</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>78.3 MPa</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>33 °C</td>
</tr>
<tr>
<td>Compressor inlet</td>
<td>Pressure</td>
<td>11.75 MPa</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>200 °C</td>
</tr>
<tr>
<td>Compressor outlet</td>
<td>Pressure</td>
<td>11.75 MPa</td>
</tr>
<tr>
<td>Turbine inlet</td>
<td>Pressure</td>
<td>11.75 MPa</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>200 °C</td>
</tr>
<tr>
<td>Turbine outlet</td>
<td>Pressure</td>
<td>7.83 MPa</td>
</tr>
</tbody>
</table>
Applications in the CVR sCO2 loop – micro heat exchangers, materials, benchmarking

- **Validation of simulation codes**
  - Validation on relevant scenarios in sCO2 loop in CVR
  - Start-up, shut down, mass change, heating/cooling power change, steady state
  - Experimental TH data obtained from sCO2 loop will be used for benchmarking, validation and further improvement of the computational codes developed.

- **Micro heat exchanger design**
  - Optimization of the printed circuit heat exchangers
  - CFD and experimental validation
  - Heat transfer and pressure drops correlations

- **Materials**
  - Testing state of the art materials used for power generation and high temperature applications, i.e. stainless steels (martensitic steel, austenitic/super-austenitic alloys, ferritic steels, duplex (austenitic + ferritic)) suitable to sCO2 environment

- **Workshops for the sCO2 community, industrial partners and students will be organized to present results and to popularize the sCO2 activities.**
Conclusion

- **CVR operates** the sCO2 experimental loop enables various experiments such as corrosion and erosion material tests, testing of heat exchangers (HX), evaluation of heat transfer coefficient and heat transfer efficiency under different energy cycle composition testing of turbomachines, valves etc. The main design parameters of the loop are: - max. temperature = 550 °C, - max. pressure = 300 bar, - max. mass flow rate = 0.35 kg/s, - heating power = 110 kW

- **CVR offers:**
  - experimental testing of the key components of the sCO2 conversion cycles
  - data for benchmark of the thermal hydraulics codes (system codes and CFD)
  - trainings in system codes and CFD
  - support in design of the sCO2 loops
  - **CVR organizes** workshops for the sCO2 community, industrial partners and students to present results and to popularize the sCO2 activities.
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