Experimental Investigation of the sCO2-HeRo Compressor

Alexander Hacks
Alexander.Hacks@uni-due.de

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Motivation

- Cut-off from power grid
- Loss of infrastructure
  - Station black-out
  - Loss of emergency power
  - Loss of heat sink
- Overheating of the nuclear core
  - Core meltdown

Photo: Tagesschau.de
The system …

Emergency scenario:

- No electrical pumps
- No heat removal by steam cycle
- Decay heat removal by sCO2-HeRo cycle
- Primary cycle in natural convection mode

✓ No core overheating
Thermodynamic parameters

Temperature / °C
Density / kg/m³
Pressure / bar
Steam-quality

h / (kJ/kg)
s / (kJ/(kg*K))

T = 200 °C

p = 117 bar
T = 33 °C

p = 78 bar

ṁ = 0.65 kg/s
Integral design

- Cold Main Flow
- Thrust Bearing
- Floating Bearing
- Hot Main Flow
- Compressor
- Alternator
- Turbine
1. **Start-up test**
   - Bringing the CO$_2$ in the system to supercritical state
   - Starting the TAC

2. **Compressor performance**
   - Validation of CFD performance map
   - Finding an inter-/extrapolation strategy for performance parameters

3. **Turbine performance**

4. **Variation of pressure in the central housing**
   - Sub- or supercritical CO$_2$
Cycle PID – Instrumentation for measurements

Performance test in SUSEN-Loop (CVR)
Position of components – Influence

3D-Model of the turbomachine test-cycle at CVR

- Liquid deposition
- Start-up of components
- Standby condition

- Release valves
- Vacuum pump
- Main cooler
- To piston pump and leakage cooler
- Oil cooler
- Oil pump
- HeRo-Turbomachine

- Heaters
- LTR HX
- HTR HX
- Vacuumb pump

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Cycle and turbomachine start-up

Standby: 2-Phase CO2

\[ p = 55-65 \text{ bar}, \]
\[ T = 15-20 \, ^\circ\text{C} \]

Heat-up & Circulation

Turbomachine heat-up: sCO2

\[ p > 74 \text{ bar} \]
\[ T > 31 \, ^\circ\text{C} \]
Cycle and turbomachine start-up

Turbomachine heat-up: sCO2
\[ p > 74 \text{ bar} \]
\[ T > 31 \degree \text{C} \]

Inventory control by booster pump & release valves

Operation point:
Compressor inlet:
\[ p = 78.3 \text{ bar} \]
\[ T = 33 \degree \text{C} \]
Cycle and turbomachine start-up

Operation point:
Compressor inlet:
\[ p = 78.3 \text{ bar} \]
\[ T = 33 \, ^\circ\text{C} \]

Testing:
Range:
\[ p = 77.3 - 79.3 \text{ bar} \]
\[ T = 31.5 - 34.5 \, ^\circ\text{C} \]
Performance test in SUSEN-Loop (CVR)

<table>
<thead>
<tr>
<th>Total Measurement Error</th>
<th>$T_{in}$</th>
<th>$T_{out}$</th>
<th>$p$</th>
<th>$\dot{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\pm 0.26 \text{ K}$</td>
<td>$\pm 0.35 \text{ K}$</td>
<td>$\pm 1.1 \text{ bar}$</td>
<td>$\pm 0.007 \text{ kg/s}$</td>
</tr>
</tbody>
</table>
Affinity laws for interpolating pressure ratio

\[ \begin{align*}
\text{Speed ratio} & \quad k_n = \frac{n_I}{n_{II}} \\
\text{Size ratio} & \quad k_d = \frac{d_I}{d_{II}} \\
\text{Density ratio} & \quad k_\rho = \frac{\rho_I}{\rho_{II}} \\
\text{Mass flow} & \quad \frac{m_I}{m_{II}} = k_d^3 \cdot k_n \cdot k_\rho \\
\text{Pressure difference} & \quad \frac{\Delta p_I}{\Delta p_{II}} = k_d^2 \cdot k_n^2 \cdot k_\rho
\end{align*} \]

Error < 2%
Validated performance map – design conditions

Mass Flow (kg/s) vs. Pressure Ratio (-)

- Surge line
- 50,000 rpm CFD
- 40,000 rpm CFD
- 30,000 rpm CFD
- 20,000 rpm CFD
- 20,000 rpm
- 30,000 rpm
- 40,000 rpm
- 50,000 rpm
Validated performance map – variation of inlet conditions

- **Surge line**
- **50,000 rpm CFD**
- **40,000 rpm CFD**
- **30,000 rpm CFD**
- **20,000 rpm CFD**
- **20,000 rpm**
- **30,000 rpm**
- **40,000 rpm**
- **50,000 rpm**

High Inlet Density: 660 kg/m³ for 79.3 bar, 31.5 °C
Nominal Inlet Density: 566 kg/m³ for 78.3 bar, 33 °C
Low Inlet Density: 328 kg/m³ for 77.3 bar, 34.5 °C
Error propagation

**Efficiency uncertainty:**

Measured: \( p, T \)

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<th>Measured parameter</th>
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<tr>
<td>Pressure Ratio ((\pi))</td>
<td>(p_{in}, \Delta p)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>(p_{in}, p_{out}, \rho_{in}, \rho_{out})</td>
</tr>
<tr>
<td>Power</td>
<td>(p_{in}, p_{out}, \rho_{in}, \rho_{out}, \dot{m}_{in})</td>
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</tbody>
</table>
Conclusions

- Heating and circulation of CO₂ in the cycle to reach the supercritical state
- Liquid CO₂ deposits at the bottom & release of CO₂ causes pipe freezing/blocking (obviously)
- Pressure losses essential for operation
- Grease lubrication incompatible with sCO₂
- Affinity laws to interpolate/extrapolate pressure ratios
- Direct density measurements required
  - Reduction of error propagation (for efficiency)
- Sealings/Insulation damaged by fast pressure drops
Thank you for your attention
Error propagation

General formula

\[ \sigma_y = \sqrt{\sum_i \left( \frac{\partial y}{\partial x_i} \cdot \sigma_{x_i} \right)^2} \]

For REFPROP (Example: \( h_{(p,T)} \))

\[ \sigma_h = \sqrt{\left( \frac{h_T}{p+\sigma_p} - h_T/p - \sigma_p \right)^2 + \left( \frac{h_p/T}{\sigma_T} - h_p/T - \sigma_T \right)^2} \]

Best measurements

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Efficiency uncertainty:

Measured: \( p, T \)