The Effect of Impurities in Rich CO$_2$ Working Fluid on the Power Output of a 10 MW sCO$_2$ Gas Turbine Power Plant

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sCO$_2$ Research at Carleton University

- Mechanical and Aerospace Engineering
  - Strong history of research and teaching in gas turbine technology
  - 4$^{th}$ year capstone projects
  - Graduate students
    - Petrusenko (2011) – The development of a high temperature sCO$_2$ corrosion test rig
    - Parks (2013) – Corrosion of candidate high temperature alloys in sCO$_2$
    - Wei (2014) – Meanline analysis of radial inflow turbines at design and off-design conditions
    - Daouk (2014) – Performance analysis and modeling of a printed circuit heat exchanger with air and carbon dioxide as working fluids
    - Martel Matos (2017) – Preliminary aerodynamic design of a sCO$_2$ centrifugal compressor
    - Strang (2018) – Aerodynamic design of a sCO$_2$ radial inflow turbine using meanline and computational methods
    - Ali (2021) – Health monitoring system for the 10 MW sCO$_2$ gas turbine power plant
    - Kaur (2021-) – Dynamic modelling of STEP cooling system/Heat exchanger modelling

- Natural Resources Canada (NRCan) – CanmetENERGY
  - R&D in clean fossil fuel technologies
  - Pilot-scale research facility
  - STEP facility support

- Design and development of advanced semi-closed and closed gas turbine cycles
sCO₂ Research at Carleton University

- 2006-11: 100 MWₑ plant
- 2011-12: 10 MWₑ plant
- 2012-16: 250 kWₜₜh pilot-scale, 10 MWₑ plant
- 2016-17: hiatus
- 2017-19: 250 kWₜₜh pilot-scale, 10 MWₑ plant, US DOE STEP Project Support
- 2019-: 100 MWₑ plant, turbomachinery scaling (50-300/500 MWₑ), US DOE STEP Project Support
Health monitoring system for (10 MWₐ) sCO₂ power plant

- Artificial neural network (ANN)
  - Capture effects of impurities and fouling effects on cycle power and efficiency
  - Property prediction
  - Compressor inlet changes on cycle efficiency
  - Effect of impurities on power output
  - Fouling effects
  - Impacts on components and efficiency

Other considerations
- Oil monitoring, vibration monitoring

10 MWₑ STEP facility/10 MWₑ Carleton Design
- “baseline” for this work
Motivation and Goal

Investigate the effect of the impurities in the rich 99% CO$_2$ working fluid for 10 MW sCO$_2$ gas turbine power plant

- **Non-condensable impurities:**
  - Nitrogen (N$_2$)
  - Oxygen (O$_2$)
  - Carbon monoxide (CO)
  - Argon (Ar)

- **Condensable impurities:**
  - Sulfur dioxide (SO$_2$)

Considering these affected impurities on:
- Power output (Operation)
- Turbomachinery degradation (Design stages)
Carleton University Brayton Cycle Loop (CUBCL)
10 MW sCO₂ gas turbine

Liquefied Saturation Line
Vapour Saturation Line
Critical Point

Turbine $\dot{m} = 104.5$ kg/s
$P = 23.72$ MPa, $PR = 2.64$
Primary heat input 22.2 MW

HTR
$P = 23.99$ MPa
$\dot{m} = 104.5$ kg/s

LTR
$P = 23.99$ MPa
$\dot{m} = 70.3$ kg/s
15.2 MW

Main compressor inlet
$T = 308.15$ K, $P = 8.55$ MPa
$\dot{m} = 70.3$ kg/s, $PR = 2.82$

Recompressor
$\dot{m} = 34.2$ kg/s
$PR = 2.76$

Cooler

LTR hot side stream
$P = 8.69$ MPa

US Department of Energy
The design point of the main compressor inlet:

- Mass flow rate ($\dot{m}$) = 70.3 kg/s
- Density ($\rho$) = 619.06 kg/m$^3$
- Pressure ratio ($P_2/P_1$) = 2.82
The pure CO$_2$ at main compressor inlet at $T=308.15$ K and $P=8.55$ MPa has a density of $\rho =619.06$ kg/ m$^3$. 
REFPROP Software

Commercial tool from the US National Institute of Standards and Technology (NIST)

Version 10 is used to calculate the CO₂ properties and mixtures

The accurate to within 0.03% of the density near critical point with Maximum error of 0.2% for the working region of the cycle
The density of the working fluid changing dramatically as a function of the total impurity concentration effects the power output

\[ \dot{m}_{\text{main-comp}} = \rho \ast A \ast v \]

Where \( \dot{m} \) mass flow rate, \( \rho \) the density and \( A \) the cross suction area.

\[ P_{\text{el}} = \dot{m}(h_6 - h_7)_{t} - \dot{m}(h_2 - h_1)_{\text{main-comp}} - \dot{m}(h_{12} - h_{11})_{\text{re-comp}} \]

Where \( P_{\text{el}} \) is electrical power and \( h \) the enthalpy.
Density reduction at the main compressor inlet at different concentrations

@ T = 308.15 K
Shows the degree of power loss due to impurities at different concentrations in rich 99% CO₂ working fluid

<table>
<thead>
<tr>
<th>Component</th>
<th>Density kg/m³</th>
<th>( \dot{m}_{\text{main,comp}} ) kg/s</th>
<th>Cycle η %</th>
<th>Power loses %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure CO₂</td>
<td>619.06</td>
<td>70.3</td>
<td>47.9</td>
<td>0</td>
</tr>
<tr>
<td>99% CO₂, 0.2%Ar, 0.2% O₂, 0.2% CO, 0.4% N₂</td>
<td>500.46</td>
<td>56.8</td>
<td>40.7</td>
<td>7.1</td>
</tr>
<tr>
<td>99% CO₂, 0.2%Ar, 0.2% O₂, 0.2% N₂, 0.4% CO</td>
<td>503.59</td>
<td>57.1</td>
<td>40.9</td>
<td>6.9</td>
</tr>
<tr>
<td>99% CO₂, 0.2%Ar, 0.2% N₂, 0.2% CO, 0.4% O₂</td>
<td>509.10</td>
<td>57.8</td>
<td>41.3</td>
<td>6.6</td>
</tr>
<tr>
<td>99% CO₂, 0.2%N₂, 0.2% O₂, 0.2% CO, 0.4% Ar</td>
<td>512.49</td>
<td>58.1</td>
<td>41.5</td>
<td>6.4</td>
</tr>
<tr>
<td>99% CO₂, 0.2%Ar, 0.2% O₂, 0.2% CO, 0.4% SO₂</td>
<td>579.16</td>
<td>65.7</td>
<td>45.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Results

Density reduction at the main compressor inlet at different concentrations

@ T= 308.15 K

Design point main compressor inlet

- Pure CO2
- 99% CO2, 0.1%N2, 0.1% O2, 0.1%CO, 0.7% Ar
- 99% CO2, 0.1%N2, 0.1% O2, 0.1%CO, 0.7% O2
- 99% CO2, 0.1%N2, 0.1% O2, 0.1%CO, 0.7% CO
- 99% CO2, 0.1%N2, 0.1% O2, 0.1%CO, 0.7% N2
- 99% CO2, 0.1%N2, 0.1% O2, 0.1%CO, 0.7% SO2
## Results

Shows the degree of power loss due to impurities at different concentrations in rich 99%CO\(_2\) working fluid

<table>
<thead>
<tr>
<th>Component</th>
<th>Density kg/m(^3)</th>
<th>(\dot{m}_{\text{main-comp}}) kg/s</th>
<th>Cycle (\eta) %</th>
<th>Power loses %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure CO(_2)</td>
<td>619.06</td>
<td>70.3</td>
<td>47.9</td>
<td>0.0</td>
</tr>
<tr>
<td>99% CO(_2), 0.1% Ar, 0.1% O(_2), 0.1%CO, 0.7% N(_2)</td>
<td>488.99</td>
<td>55.5</td>
<td>40.1</td>
<td>7.8</td>
</tr>
<tr>
<td>99% CO(_2), 0.1% Ar, 0.1% O(_2), 0.1%N(_2), 0.7% CO</td>
<td>498.14</td>
<td>56.5</td>
<td>40.6</td>
<td>7.3</td>
</tr>
<tr>
<td>99% CO(_2), 0.1% Ar, 0.1% N(_2), 0.1%CO, 0.7% O(_2)</td>
<td>514.77</td>
<td>58.4</td>
<td>41.6</td>
<td>6.3</td>
</tr>
<tr>
<td>99% CO(_2), 0.1%N(_2), 0.1% O(_2), 0.1%CO, 0.7% Ar</td>
<td>524.7</td>
<td>59.5</td>
<td>42.2</td>
<td>5.7</td>
</tr>
<tr>
<td>99% CO(_2), 0.1% Ar, 0.1% O(_2), 0.1%CO, 0.7% SO(_2)</td>
<td>614.87</td>
<td>69.8</td>
<td>47.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>
The effect of SO₂ and N₂ concentrations of 1% on the density of rich 99% CO₂ working fluid

@ T= 308.15 K

Design point main compressor inlet

Density (kg/m³)

Pressure (MPa)

Pure CO₂

1% N₂

1% SO₂
The effects of SO₂ and N₂ concentrations of 1% on the density and overall cycle efficiency of rich 99% CO₂

<table>
<thead>
<tr>
<th>Component</th>
<th>Density kg/m³</th>
<th>$\dot{m}_{\text{main comp}}$ kg/s</th>
<th>Cycle η %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure CO₂</td>
<td>619.06</td>
<td>70.3</td>
<td>47.9</td>
</tr>
<tr>
<td>99% CO₂, 1% N₂</td>
<td>478.11</td>
<td>54.2</td>
<td>39.4</td>
</tr>
<tr>
<td>99% CO₂, 1% SO₂</td>
<td>642.56</td>
<td>72.9</td>
<td>49.4</td>
</tr>
</tbody>
</table>
Conclusions

Analysing the effect of impurities of the working fluid would beneficial the 10 MW sCO$_2$ gas turbine designers and operators.

- **Non-condensable impurities:**
  - The present of impurities N$_2$, O$_2$, CO and Ar in the working fluid effected the turbine performance
  - N2 is found as an affective impure on the power output
  - A mixture of 99% CO$_2$ and 1% N$_2$ caused maximum density reduction almost 23% and reduced the cycle efficiency to 8.5%.

- **Condensable species:**
  - Concentration of 1% of Sulfur dioxide in 99% CO$_2$ would:
    - Increase the density by 23.5 kg/m$^3$
    - and the power output up to 1.4%
  - An increase in SO$_2$ concentration in supercritical CO$_2$ region rapidly degrades turbomachinery’s component by corrosion.
  - Understanding the concentration of impurities is vital to avoiding corrosion-related damage and improving the efficiency

- **Other considerations:**
  - Effect on cycle operation – shift in operation points
  - Cycle performance, temperatures
Thank you
Questions