An Assessment of Supercritical CO₂ Power Cycles Integrated with Generic Heat Sources

Chuck White, Noblis
Wally Shelton, NETL
Richard Dennis, NETL

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Overview

- Baseline process – sCO$_2$ recompression Brayton cycle
- Sensitivity analyses: optimizing efficiency
- Indirect cost variables
- Summary
Recompression Brayton Cycle
# Recompression Brayton Cycle

*Parameters for Baseline Cycle*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat source</td>
<td>Generic</td>
</tr>
<tr>
<td>Nominal thermal input</td>
<td>64 MMBtu/hr</td>
</tr>
<tr>
<td>Turbine exit pressure</td>
<td>1350 psia</td>
</tr>
<tr>
<td>CO$_2$ cooler temperature</td>
<td>35 °C (95 °F)</td>
</tr>
<tr>
<td>Turbine isentropic efficiency</td>
<td>0.927</td>
</tr>
<tr>
<td>Compressor isentropic efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>Cycle pressure drop</td>
<td>60 psia</td>
</tr>
<tr>
<td>Minimum temperature approach</td>
<td>5.6 °C (10 °F)</td>
</tr>
<tr>
<td>Turbine inlet temperature</td>
<td>700 °C (1292 °F)</td>
</tr>
<tr>
<td>Nominal compressor pressure</td>
<td>5100 psia</td>
</tr>
<tr>
<td>Nominal pressure ratio</td>
<td>3.9</td>
</tr>
<tr>
<td>Nominal CO$_2$ cooler bypass fraction</td>
<td>0.283</td>
</tr>
</tbody>
</table>
Recompression Brayton Cycle
Recompression Brayton Cycle

*Stream table at compressor pressure 5100 psia*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main compressor power (MW)</td>
<td>2.1</td>
</tr>
<tr>
<td>Bypass compressor power (MW)</td>
<td>2.0</td>
</tr>
<tr>
<td>Turbine power (MW)</td>
<td>14.1</td>
</tr>
<tr>
<td>Net power (MW)</td>
<td>10.0</td>
</tr>
<tr>
<td>Recuperator stage 1 duty (MMBtu/hr)</td>
<td>76.5</td>
</tr>
<tr>
<td>Recuperator stage 2 duty (MMBtu/hr)</td>
<td>40.5</td>
</tr>
<tr>
<td>Hot source duty (MMBtu/hr)</td>
<td>64.4</td>
</tr>
<tr>
<td>CO₂ cooler duty (MMBtu/hr)</td>
<td>30.3</td>
</tr>
</tbody>
</table>
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Sensitivity to CO$_2$ cooler bypass fraction

![Graph showing the sensitivity of cycle efficiency to CO$_2$ cooler bypass fraction. The graph indicates a positive correlation between the bypass fraction and cycle efficiency.]
Recompression Brayton Cycle

*T-H diagram for recuperated Brayton cycle - bypass fraction = 0.000*
Recompression Brayton Cycle

T-H diagram for recuperated Brayton cycle - bypass fraction = 0.283

- Temperature (°F)
- Enthalpy change (MMBtu/hr)

- Hot Side
- Cold Side
Recompression Brayton Cycle

*Sensitivity to pressure ratio*

![Graph showing the sensitivity of cycle efficiency to pressure ratio.](image-url)
Recompression Brayton Cycle

Sensitivity to turbine exit pressure

![Graph showing cycle efficiency sensitivity to turbine exit pressure](image)
Recompression Brayton Cycle

*Sensitivity to turbine inlet temperature*

Cycle efficiency (%) vs. Pressure ratio for different turbine inlet temperatures:
- **Red line**: TIT = 760 °C
- **Blue line**: TIT = 700 °C
- **Orange line**: TIT = 650 °C
- **Purple line**: TIT = 600 °C
- **Green line**: TIT = 550 °C
Recompression Brayton Cycle

Sensitivity to turbine inlet temperature
Recompression Brayton Cycle

Sensitivity to compressor efficiency

![Graph showing cycle efficiency vs. pressure ratio for different compressor efficiencies.](image-url)
Recompression Brayton Cycle

Sensitivity to turbine efficiency

![Graph showing cycle efficiency vs. pressure ratio for different turbine efficiencies.](image)

- Cycle efficiency (%) vs. Pressure ratio
- Lines color-coded for different turbine efficiencies:
  - Efftrb = 1.00 (green)
  - Efftrb = 0.95 (purple)
  - Efftrb = 0.927 (blue)
  - Efftrb = 0.90 (red)
  - Efftrb = 0.85 (orange)
  - Efftrb = 0.80 (brown)
  - Efftrb = 0.75 (teal)
Recompression Brayton Cycle

*Sensitivity to turbomachinery efficiency*

![Graph showing the relationship between isentropic efficiency and cycle efficiency for compression (Comp) and turbine (Turb) components. The graph indicates how cycle efficiency increases with increasing isentropic efficiency.]
Recompression Brayton Cycle

*Sensitivity to pressure drop*

![Graph showing cycle efficiency vs. pressure ratio for different pressure drops.](image)
Recompression Brayton Cycle

*Sensitivity to pressure drop*

![Graph showing the sensitivity of cycle efficiency to pressure drop. The graph depicts a linear relationship where cycle efficiency decreases as cycle pressure drop increases. The x-axis represents cycle pressure drop (psia) ranging from 0 to 200, and the y-axis represents cycle efficiency (%) ranging from 54% to 51%. The line on the graph indicates a decrease in efficiency with increasing pressure drop.]
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Sensitivity to minimum temperature approach

Cycle efficiency (%) vs. Pressure ratio for different Tapp values:
- Tapp = 0 °F
- Tapp = 10 °F
- Tapp = 20 °F
- Tapp = 30 °F
- Tapp = 40 °F
Recompression Brayton Cycle

*Sensitivity to minimum temperature approach*

![Graph showing the relationship between cycle efficiency and minimum temperature approach. The graph depicts a linear decrease in cycle efficiency as the minimum temperature approach increases.](image)
Recompression Brayton Cycle

*Sensitivity to CO₂ cooler temperature*

![Graph showing the sensitivity of Efficiency to CO₂ cooler temperature across different pressure ratios and temperatures. The graph plots Efficiency (%) on the y-axis and Pressure ratio on the x-axis. The legend identifies different CO₂ cooler temperatures (Tc) ranging from 32°C to 45°C, each represented by a different line color.]
Recompression Brayton Cycle

Sensitivity to CO₂ cooler temperature

Cycle efficiency (%) vs. CO₂ cooler temperature (°C)
Indirect cost variables

- Provide a “surrogate” for inferring relative cost impacts
- Reliable costs for sCO$_2$ recompression Brayton cycle not available
- Process variables or derived quantities that have a strong influence on cost
- Used to determine if a cycle configuration is on a steep part of the sensitivity curve
<table>
<thead>
<tr>
<th>Cycle component</th>
<th>Indirect cost metric</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Cycle</td>
<td>Temperature</td>
<td>Materials selection</td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>Ambiguous indicator</td>
</tr>
<tr>
<td></td>
<td>Cycle efficiency</td>
<td>Inverse operating costs</td>
</tr>
<tr>
<td></td>
<td>Mass flow rate, Specific power</td>
<td>Indicator of overall plant size</td>
</tr>
<tr>
<td>Compressor/Turbine</td>
<td>Power, Mass flow</td>
<td>Indicator of unit size</td>
</tr>
<tr>
<td></td>
<td>Pressure ratio</td>
<td>Number of stages required</td>
</tr>
<tr>
<td></td>
<td>Inlet volumetric flow</td>
<td>Indicator of inlet size</td>
</tr>
<tr>
<td>Recuperator</td>
<td>Total heat duty, LMTD (UA)</td>
<td>Indicator of unit size</td>
</tr>
<tr>
<td>Heat source</td>
<td>Total heat duty, LMTD (UA), CO$_2$ thermal capacitance</td>
<td>Indicator of unit size</td>
</tr>
</tbody>
</table>
Recompression Brayton Cycle

Main compressor inlet volumetric flow

![Graph showing the relationship between compressor flow (ft³/s) and pressure ratio.](image-url)
Recompression Brayton Cycle

*Turbine inlet volumetric flow*

![Graph showing the relationship between turbine flow (ft³/s) and pressure ratio. The graph indicates a significant decrease in turbine flow as the pressure ratio increases.]
Recompression Brayton Cycle

Total recuperator duty

Graph showing the relationship between recuperator duty (MMBtu/hr) and pressure ratio.
Recompression Brayton Cycle

Total recuperator UA

![Graph showing the relationship between UA (MBtu/hr/ft²) and Pressure ratio.]
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*Hot source duty*

![Graph showing recompression Brayton cycle with hot source duty vs pressure ratio.](image-url)
Recompression Brayton Cycle

Specific power

![Graph showing the relationship between specific power (W/lb/hr) and pressure ratio. The graph indicates an increasing specific power with increasing pressure ratio.](image-url)
Recompression Brayton Cycle

$CO_2$ flow

![Graph showing CO$_2$ flow versus Pressure ratio. The graph indicates a decrease in CO$_2$ mass flow with an increase in Pressure ratio.](image-url)
Summary

• sCO₂ recompression Brayton cycles appear to offer a number of benefits including high cycle efficiency

• The baseline cycle operating parameters offer a relatively high efficiency operation

• Non-ideal properties of CO₂ near the critical region make the recompression cycle advantageous
Summary

- Care must be taken to assure that cycle operation is not unduly sensitive to perturbations

- Sensitivity studies suggest the cycle may offer benefits in a wide variety of applications and settings

- The baseline cycle operating parameters do not appear to be in a region of pronounced cost sensitivity
**SCO₂ Power Cycles for Coal-Based Power Plants**

- Applicable to multiple coal-based platforms (air and oxygen-fired, PC, CFB, PFBC)
  - Coal combustor modifications (and associated costs) needed to accommodate SCO₂ heating and to match temperature-enthalpy profile of SCO₂ cycles of interest

- Efficiency improvements afforded by SCO₂ power cycles have the potential to substantially reduce the cost of electricity (COE) of coal-based systems:
  - Increase in efficiency reduces fuel costs and base plant capital costs per MW of output
  - If combustor + power island costs = steam cycle:
    - ↑ 5 efficiency percentage pts => ↓ COE by >10%
  - For a breakeven COE:
    - ↑ 1 efficiency percentage pt allows for ↑ 12% in combustor + power island costs relative to steam cycle