Analysis of Supercritical CO$_2$ Brayton Cycle Recuperative Heat Exchanger Size and Capital Cost with Variation of Layout Design

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What is Supercritical CO\textsubscript{2}?

<table>
<thead>
<tr>
<th>$T_{\text{critical}}$ (°C/°F)</th>
<th>$P_{\text{critical}}$ (MPa/kPSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.0 / 87.9</td>
<td>7.4 / 1.1</td>
</tr>
</tbody>
</table>

$T_{\text{critical}}$ and $P_{\text{critical}}$ values from Span and Wagner (1996).
# Brayton Cycle Heat Exchangers

<table>
<thead>
<tr>
<th>Cycle Type</th>
<th>Compressors</th>
<th>Turbines</th>
<th>Recuperators</th>
<th>Coolers</th>
<th>IHXs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Recuperative</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pre-Compression</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Partial Cooling w/Improved Regen.</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cascaded Reheat</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Recompression</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

- Cycle layout variations can improve efficiency
- Can increase complexity and budget
- **Size and capital cost of recuperative heat exchangers**

Angelino (1969)  
Dostal *et al.* (2004)  
Wright *et al.* (2010)  
Conboy *et al.* (2012)  
Iverson *et al.* (2013)  
Ahn *et al.* (2015)
Printed-Circuit Heat Exchangers

Stack Platelets
ABAB . . . BABA

COLD
HOT
Diffusion Bonding Fabrication Technology

What:
• Highly reliable, solid-state welding process
• No interface filler material needed

How:
• Controlled environment furnace promotes grain growth
• Dynamic, time-dependent load applied

Outcome:
• Achieved parent material strength
• ‘Welds’ all interfaces while preserving geometry
Agenda

1. Introduction
2. Power Cycle Layouts
3. Modeling Approach and Methodology
4. Recuperative Heat Exchanger Cost Variables
5. Results and Discussion
6. Conclusions and Future Work
Simple Recuperative Brayton Cycle

- Simple layout
- Single recuperator
- Latent heat energy sources or heat flux sources
Recompression Brayton Cycle

- Compression through two stages of compressors
- HTR and LTR heat recovery by splitting vastly different Cp
- Nuclear or solar thermal based heat flux sources
Cascaded Reheat Brayton Cycle

- Expansion through two stages of turbines
- Attempts to utilize all heat source energy
- Fossil fuel or waste heat
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5. Results and Discussion
6. Conclusions and Future Work
Summary of Cycle Conditions and Assumptions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Simple</th>
<th>Recomp.</th>
<th>Casc. Reheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Output ($MW_{th}$)</td>
<td>50 $MW_{th}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine Power Percentage (%)</td>
<td>100%</td>
<td></td>
<td>Split &amp; Varied</td>
</tr>
<tr>
<td>Thermal Efficiency (%)</td>
<td>Calc., 45%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$sCO_2$ Flow Rate (kg-s$^{-1}$)</td>
<td>Calculated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine Inlet Temperature (°C)</td>
<td>650 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor Inlet Temperature (°C)</td>
<td>35 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor Outlet Pressure (MPa)</td>
<td>25 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor Ratio (-)</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- *Engineering Equation Solver* (EES) platform V.10.295-3D (Klein 2017)
- EOS for CO$_2$ as developed by Span and Wagner (1996)
- Negligible: $\Delta P$, PE, KE
- Isentropic efficiency = 100% (ideal)
Methodology

\[ \eta_{cycle} = 100 \times \left( \frac{\sum \dot{W}_{TURB} - \sum \dot{W}_{COMP}}{\dot{Q}_{IHX}} \right) \]

\[ \frac{dE_{cv}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum \dot{m} \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \sum \dot{m} \left( h_o + \frac{V_o^2}{2} + gz_o \right) \]

\[ \dot{W}_{TURB} = \dot{m} \times (h_i - h_o) \]

\[ \dot{W}_{COMP} = \dot{m} \times (h_o - h_i) \]

\[ \dot{Q}_{IHX} = \dot{m} \times (h_o - h_i) \]
Methodology Cont’d

\[
\dot{Q}_{REC,h} = \dot{m} \times (hi - ho)
\]

\[
\dot{Q}_{REC,c} = \dot{m} \times (ho - hi)
\]

\[
\dot{Q}_{REC} = \dot{Q}_{REC,h} = \dot{Q}_{REC,c}
\]

\[
\dot{Q}_{REC} = UA_{REC} \times LMTD
\]

\[
\varepsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{maximum}} = \frac{h_{h,i} - h_{h,o}}{h_{h,i} - h_{c,i}^*}
\]

\[h_{c,i}^* = f(T_{c,i}, P_h)\]

Sharma et al. (2017)
1. Introduction

2. Power Cycle Layouts

3. Modeling Approach and Methodology

4. Recuperative Heat Exchanger Cost Variables

5. Results and Discussion

6. Conclusions and Future Work
Heat Exchanger Capital Cost Variables

\[ \dot{Q}_{REC} = UA_{REC} \times LMTD \]

\[ \Delta P = Lf \frac{\rho}{2} \frac{V}{D_H} + \sum K_{minor} \]
Recuperative Heat Exchanger Capital Cost

NOTE: cost metrics are a function of a limited range of process conditions and should not be universally applied to all heat exchangers
1. Introduction
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Results and Discussion

![Graph showing power cycle efficiency vs. approach temperature with different cycle types and a 15.5% difference in efficiency.]

![Graph showing recuperator UA requirement vs. approach temperature with different cycle configurations.]

<table>
<thead>
<tr>
<th>( \dot{W}_{TURB} )</th>
<th>( \dot{m}_{SC02} )</th>
<th>( T_{TURB,i} )</th>
<th>( T_{COMP,i} )</th>
<th>Split-Flow</th>
<th>( R_{COMP} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MW(_{th})</td>
<td>278.1 kg-s(^{-1})</td>
<td>650 °C</td>
<td>35 °C</td>
<td>0.50 (-)</td>
<td>3.0 (-)</td>
</tr>
</tbody>
</table>
## Results and Discussion Cont’d

<table>
<thead>
<tr>
<th>$\dot{W}_{TURB}$</th>
<th>$T_{TURB,i}$</th>
<th>$T_{COMP,i}$</th>
<th>$R_{COMP}$</th>
<th>$\Delta T_{HTR/LTR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MW$_{th}$</td>
<td>650 °C</td>
<td>35 °C</td>
<td>3.0 (-)</td>
<td>10 K</td>
</tr>
</tbody>
</table>

![Graph](image)

- Recompression HTR UA
- Recompression LTR UA
- Cascade HTR UA
- Cascade LTR UA
### Results and Discussion Cont’d

<table>
<thead>
<tr>
<th>$\dot{W}_{TURB}$</th>
<th>$T_{TURB,i}$</th>
<th>$T_{COMP,i}$</th>
<th>$R_{COMP}$</th>
<th>$\Delta T$ HTR/LTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>650 °C</td>
<td>35 °C</td>
<td>3.0 (-)</td>
<td>10 K</td>
</tr>
</tbody>
</table>

![Graph](graph.png)

- Recompression HTR Temperature Approach
- Recompression LTR Temperature Approach
- Cascade LTR Temperature Approach
- Cascade HTR Temperature Approach
Results and Discussion Cont’d

<table>
<thead>
<tr>
<th>$\dot{W}_{TURB}$</th>
<th>$T_{TURB,i}$</th>
<th>$T_{COMP,i}$</th>
<th>$R_{COMP}$</th>
<th>$\Delta T_{HTR/LTR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MW$_{th}$</td>
<td>650 °C</td>
<td>35 °C</td>
<td>3.0 (-)</td>
<td>10 K</td>
</tr>
</tbody>
</table>

- Recompression HTR Effectiveness
- Recompression LTR Effectiveness
- Cascade LTR Effectiveness
- Cascade HTR Effectiveness
Results and Discussion Cont’d

<table>
<thead>
<tr>
<th>$\dot{W}_{TURB}$</th>
<th>$\eta_{cycle}$</th>
<th>$T_{TURB,i}$</th>
<th>$T_{COMP,i}$</th>
<th>$R_{COMP}$</th>
<th>$\Delta T \ HTR/LTR$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MW$_{th}$</td>
<td>45 (%)</td>
<td>650°C</td>
<td>35°C</td>
<td>3.0 (-)</td>
<td>10 K</td>
</tr>
</tbody>
</table>
## Results and Discussion Cont’d

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recompression</th>
<th>Cascaded Reheat</th>
<th>Recomp. vs. Cascade</th>
</tr>
</thead>
<tbody>
<tr>
<td>IHX Duty (MW)</td>
<td>60.9 MW</td>
<td>97.5 MW</td>
<td>+60%</td>
</tr>
<tr>
<td>Comp. Work (MW); MC, RC</td>
<td>-2.4 MW, -20.2 MW</td>
<td>-6.1 MW</td>
<td>-73%</td>
</tr>
<tr>
<td>Turb. Work (MW); HT, LT</td>
<td>50 MW</td>
<td>21.4 MW, 28.6 MW</td>
<td>0%</td>
</tr>
<tr>
<td>$X$ (-)</td>
<td>0.6558</td>
<td>0.5148</td>
<td>-21.5%</td>
</tr>
<tr>
<td>Mass Flow (kg-s$^{-1}$)</td>
<td>278.1 kg-s$^{-1}$</td>
<td>245.7 kg-s$^{-1}$</td>
<td>-11.7%</td>
</tr>
<tr>
<td>HTR Duty (MW)</td>
<td>45.4 MW</td>
<td>44.4 MW</td>
<td>-2.2%</td>
</tr>
<tr>
<td>HTR UA (kW-K$^{-1}$)</td>
<td>3,235 kW-K$^{-1}$</td>
<td>1,099 kW-K$^{-1}$</td>
<td>-66%</td>
</tr>
<tr>
<td>HTR Effectiveness (%)</td>
<td>93.4%</td>
<td>90.2%</td>
<td>-3.4%</td>
</tr>
<tr>
<td>HTR LMTD (K)</td>
<td>14.0 K</td>
<td>40.4 K</td>
<td>+186%</td>
</tr>
<tr>
<td>LTR Duty (MW)</td>
<td>41.7 MW</td>
<td>16.8 MW</td>
<td>-59.7%</td>
</tr>
<tr>
<td>LTR UA (kW-K$^{-1}$)</td>
<td>799 kW-K$^{-1}$</td>
<td>734 kW-K$^{-1}$</td>
<td>-8.1%</td>
</tr>
<tr>
<td>LTR Effectiveness (%)</td>
<td>44%</td>
<td>68%</td>
<td>+54.5%</td>
</tr>
<tr>
<td>LTR LMTD (K)</td>
<td>52.2 K</td>
<td>23.0 K</td>
<td>-56%</td>
</tr>
<tr>
<td>LTR Cost Ratio (-)</td>
<td>1.00</td>
<td>0.92</td>
<td>-8.1%</td>
</tr>
</tbody>
</table>
Conclusions

• Thermodynamic analysis of recuperative heat exchangers
  • Simple recuperative
  • Recompression
  • Cascaded reheat

• Variation of approach temperature shows limitation of cascaded reheat cycle

• Split flow magnitude show interesting difference in UA requirements between cycles

• Single cost metric will not provide accurate heat exchanger cost
  • Too many variables
  • Case-by-case basis
Future Work

• Discretize recuperative heat exchanger

• Evaluate different cycle parameter sets between cycle

• Complete full heat exchanger cost analysis
  • PCHE layout design
  • Mechanical design
  • Optimization of core blocks
  • Large vs. small furnace diffusion bonding


Questions?

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