Polygon Expansion Engine
Waste Heat Energy SCO2 Recovery
Cycle Thermodynamic Analysis and Component Design

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Outline

- Introduction
- Design Concept
- Thermodynamic Modeling
- Manufacturing Methodology
- Component Stress Analysis
- Conclusions
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Introduction

- Approximately 280 GW of waste heat is estimated to be expelled annually by
  - Could result in $70–$150 billion in savings if salvaged
  - On this scale, any efficiency increase will result in large savings

- $CO_2$ offers unique properties as a working fluid for a cycle
  - Relatively low temperatures for supercritical state
  - Unique challenges for pressures and viscosities
    - High pressure ranges, 4–5 times max pressure in typical diesel engines
    - Viscosity poses problems for sealing, dry gas mechanical seals needed

- Relatively recent hardware innovations and green energy initiatives have sparked interest in applications
Introduction

- It has recently been recognized that a large quantity of waste heat is generated annually, and thus represents a large opportunity for energy savings.

- With burgeoning research in cycles which utilize supercritical carbon dioxide as a unique working fluid; herein an optimized thermodynamic cycle development was proposed that would center around a novel expansion device for extracting power from the $\text{SCO}_2$ working fluid.
Introduction

- Passive and active components in the system
  - Passive: Heat exchangers
    - Well formulated design criteria readily available, especially for single phase flow
  - Active: Pump/Compressor and Expander
    - Pump/Compressor technology has existed for 20 years for dealing with super-critical carbon dioxide
    - Expander design has become an industry goal for such processes
  - Expander design
    - High specific power goals
    - Compatibility with SCO2
Design Concept

- The original engine design stemmed from a Polygon engine project sponsored by Butte Industries, Inc. [1,2] while the current evolution of the design stems from the works published in [3–5]
The Mollier diagram for the expansion process in conjunction with the waste heat recovery cycle is shown below in Figure 2.

Figure 2. Mollier Diagram for SC02 Waste Heat Recovery Cycle [2]
4th Intl. SC02 Power Cycles Symposium, Pittsburgh, PA, 2014  9/10/2014
The pertinent thermodynamic state points for the expansion engine are summarized in Table 1.

Table 1. Pertinent Thermodynamic State Points for SCO2 Waste Heat Recovery Cycle [2]

<table>
<thead>
<tr>
<th>State Points (cf. Figure 2)</th>
<th>T (K)</th>
<th>P (MPa)</th>
<th>Density (kg/cu m)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (kJ-kg-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>308</td>
<td>12.4</td>
<td>776.61</td>
<td>278.19</td>
<td>1.23</td>
</tr>
<tr>
<td>2</td>
<td>319</td>
<td>20.0</td>
<td>810.49</td>
<td>289.38</td>
<td>1.24</td>
</tr>
<tr>
<td>3</td>
<td>417</td>
<td>20.0</td>
<td>338.83</td>
<td>413.32</td>
<td>1.86</td>
</tr>
<tr>
<td>4</td>
<td>473</td>
<td>20.0</td>
<td>258.82</td>
<td>597.79</td>
<td>2.05</td>
</tr>
<tr>
<td>5</td>
<td>436</td>
<td>12.4</td>
<td>176.78</td>
<td>577.23</td>
<td>2.08</td>
</tr>
<tr>
<td>6</td>
<td>328</td>
<td>12.4</td>
<td>537.76</td>
<td>353.29</td>
<td>1.47</td>
</tr>
</tbody>
</table>
Design Concept

- Cycle efficiency analysis

Figure 3. Cycle efficiency based on temperature drop over heat exchanger [2].
Design Concept

- **Specifications**
  - SCO2 Mass Flow Rate approx. $30 \text{ gm/s} = 238 \text{ lb/hr}$
  - 300 RPM operating speed
  - 0.8~1.1 kW power generation

- The modular design shown in Figure 1 allows the ability to have multiple engines stacked in series as shown below in Figure 4

![Stacked Polygon Expansion Engine Design Concept](image)

Figure 4. Stacked Polygon Expansion Engine Design Concept [3,4].
A key component of the system design was the modeling of chamber pressure as this would drive all design modifications. The modeling was centered around a polytropic model which spurred a new methodology for determining the polytropic index as detailed in [5]. The chamber thermodynamic behavior is detailed in Figure 5 through Figure 7 below.
Thermodynamic Modeling

Figure 5. Pressure Volume Diagram of Expansion Process [5].

Figure 6. Pressure Enthalpy Diagram of Expansion Process [5].

Figure 7. Temperature Entropy Diagram of Expansion Process [5].
Thermodynamic Modeling

- $P, T, \rho$ as a function of stroke during expansion process
  - Note: SCO2 $\rho$ remains below critical state during expansion, while $p$ & $T$ remain above critical state.

Figure 8. Pressure vs. Stroke [5].

Figure 9. Temperature vs. Stroke [5].

Figure 10. Density vs. Stroke [5].
The nominal polytropic index was found per [5]

\[
\frac{(n - 2k_{avg} + 1)}{(1 - n)} \left[ (2\zeta x_f + 1)^{1-n} - 1 \right] = \frac{2\rho_o (u(\rho, T) - u_o) (k_{avg} - 1)}{P_o}
\]

\( k = \) Ratio of specific heats

\( n = \) Polytropic Exponent

\( u(\rho, T) = \) Internal Energy of SCO2 per NIST REFPROPS

### Table 2. Nominal Polytropic Index Iteration Procedure [5].

<table>
<thead>
<tr>
<th>Iteration</th>
<th>( T ) (K)</th>
<th>( P ) (MPa)</th>
<th>( T_{\text{error}} ) (%)</th>
<th>( P_{\text{error}} ) (%)</th>
<th>( k_{avg}/n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>436</td>
<td>12.4</td>
<td>8</td>
<td>35</td>
<td>1.580/1.302</td>
</tr>
<tr>
<td>2</td>
<td>420</td>
<td>11.0</td>
<td>4</td>
<td>20</td>
<td>1.600/1.304</td>
</tr>
<tr>
<td>3</td>
<td>405</td>
<td>9.2</td>
<td>0.02</td>
<td>0.02</td>
<td>1.615/1.306</td>
</tr>
</tbody>
</table>
The manufacturing process selection was crucial to obtaining a design that could be produced.

An initial trade study was performed to determine the feasibility of using silicon carbide (SiC) due to low material costs, availability, and potential mechanical properties but was ultimately turned down due to lack of material standardization and machining costs involved when produced with the required strength specifications.
Due to the relatively low operating temperatures, various steels were chosen to meet loading requirements and provide thermal expansion uniformities.

The present design is shown in Figure 11 as an assembly rendering.
Manufacturing Methodology

- Figure 12 through Figure 16 show detailed drawings of the primary components comprising the expansion engine design.
Manufacturing Methodology

Figure 13. Detailed Drawing and Bill of Materials for Disc Subassembly

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>Material</th>
<th>Finish</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2300-01A_a</td>
<td>back disk</td>
<td>AISI 1020</td>
<td>SAND CAST/MACHINED</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2300-01A_b</td>
<td>main shaft support</td>
<td>AISI 1045 Steel, cold drawn</td>
<td>CNC MACHINED</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>main shaft support</td>
<td>AISI 1045 Steel, cold drawn</td>
<td>CNC MACHINED</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2300-02A_a</td>
<td>front disk</td>
<td>AISI 1020</td>
<td>SAND CAST/MACHINED</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>front disk</td>
<td>AISI 1020</td>
<td>SAND CAST/MACHINED</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 14. Detailed Drawing and Bill of Materials for Disc Crankshaft Subassembly

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>Material</th>
<th>Finish</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2300-01A_b</td>
<td>crank bearing support, V2</td>
<td>AISI 1045 Steel, cold drawn</td>
<td>SAND CASTED</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2300-02A_b</td>
<td>external case, crank support, V2</td>
<td>AISI 1045 Steel, cold drawn</td>
<td>CNC MACHINED</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2300-03A_b</td>
<td>crank shaft</td>
<td>AISI 1020</td>
<td>SAND CASTED/MACHINED</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>crank bearing cover</td>
<td>AISI 1045 Steel, cold drawn</td>
<td>CNC MACHINED</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>crank bearing cover</td>
<td>AISI 1045 Steel, cold drawn</td>
<td>CNC MACHINED</td>
<td>2</td>
</tr>
</tbody>
</table>
Manufacturing Methodology

Figure 15. Detailed Drawing and Bill of Materials for Pushrod Subassembly

Figure 16. Detailed Drawing and Bill of Materials for Piston Rod Subassembly
Component Stress Analysis

- Finite element analysis using NX software was employed to predict the stresses in the major components of the SCO2 Polygon Expansion Engine.
- Figure 17 through Figure 19 show typical results.
Component Stress Analysis

Figure 17. FEA Stress Analysis for Disc Assembly

Figure 18. FEA Stress Analysis for Crankshaft Assembly

Figure 19. FEA Stress Analysis for Piston–head Assembly
Detailed precision hand calculations were also performed at the machine component level based on the practices outlined in Shigley and Mischke [6]. Relevant findings are highlighted below in Table 3.

<table>
<thead>
<tr>
<th>Engine Component</th>
<th>Stress Mode</th>
<th>Max. Stress (ksi)</th>
<th>F.S. (Static/Fatigue)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrist Pin</td>
<td>Bending</td>
<td>98</td>
<td>2.04/1.53</td>
</tr>
<tr>
<td>Connecting Rod</td>
<td>Compression</td>
<td>27</td>
<td>2.90/2.53</td>
</tr>
<tr>
<td>Center Shaft</td>
<td>Compression</td>
<td>48</td>
<td>2.93/1.50</td>
</tr>
<tr>
<td>Disc</td>
<td>Bending</td>
<td>16</td>
<td>4.57/4.95</td>
</tr>
</tbody>
</table>
Conclusions

This paper summarizes the thermodynamic modeling, machine design layout and component level stress analysis of a Polygon Expansion Engine for use in a SCO2 Waste Heat Recovery Cycle

Working design
- High specific power
- Modular design for expandability

Issues
- Appropriate bearing choices
- Good lubrication but unbounded by appropriate bearings

Bottom line: Viable design with a few unbounded issues

Future work will include
- Analysis and design of lubrication system for the engine
- Engaging venture capitalists and National Labs in order to sponsor the funding required to fabricate a proto-type working engineering model of the engine
References


