Turbo-Machinery Considerations Using Super-Critical Carbon Dioxide Working Fluid for a Closed Brayton Cycle

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Machinery Discussion

- Large Scale ~300 Mwe Rotating Equipment Design
  - Compressors
  - Turbine
  - Seal Options
  - Bearing Options
  - Generator Option

- Small Scale ~ 280 kWe System Design
  - Compressors
  - Turbine
  - Seal Options
  - Bearing Options
  - Generator Option
Cycle Design Is the Input to the Turbomachinery Design

**MIT Cycle** (V. Dostal, M.J. Driscoll, P. Hejzlar, and N.E. Todreas, 2002 (MIT-ANP-TR-090))

**Turbine**
- Mass Flow=3485 kg/sec
- Pin=19.83 MPa
- Tin=550 deg C
- Pout=7.90 MPa

**Main Compressor**
- Mass Flow=2091 kg/sec
- Pin=7.69 MPa
- Tin=32 deg C
- Pout=20 MPa

**Re-Compressor**
- Mass Flow=1349 kg/sec
- Pin=7.70 MPa
- Tin=69.69 deg C
- Pout=20 MPa

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**Figure 1.2 Reference Cycle State Points for 300MWe**

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Large System
Ground Rule: Industry Acceptance Is Important

• Make the Machinery Look Like Conventional Power Plants If Possible (Generate Industry Interest)
  – 3600 RPM (GE Makes a 3600 RPM Hydrogen Cooled Generator @ ~300 Mwe)
  – Single Shaft
  – Oil Lubricated Hydrodynamic Bearings (Tilt Pad or Elliptical)
  – Seals (Acceptable on Steam and Gas Turbines)
  – Horizontal Shaft
Ns-Ds Diagram Compressors (English Units)

Highest Efficiency Speed and Diameter

Large System
Main Compressor (Large System)

3-Stage Radial Efficiency is 87%

### MAIN COMPRESSOR PERFORMANCE

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Pressure (MPa)</th>
<th>Density (kg/m³)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (kJ/kg-K)</th>
<th>Cp (kJ/kg-K)</th>
<th>Stage US Eff.</th>
<th>Stage US Ns</th>
<th>Overall US Ns</th>
<th>Overall L2 ft/s</th>
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<td>32</td>
<td>7.69</td>
<td>598.81</td>
<td>306.81</td>
<td>1.3463</td>
<td>15.813</td>
<td>1.20</td>
<td>154</td>
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<td>41.649</td>
<td>10.766</td>
<td>647.38</td>
<td>311.74</td>
<td>1.3483</td>
<td>4.7145</td>
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<td>41.803</td>
<td>10.766</td>
<td>644.8</td>
<td>312.48</td>
<td>1.3506</td>
<td>4.7558</td>
<td>0.99</td>
<td>128</td>
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<tr>
<td>51.164</td>
<td>14.803</td>
<td>684.11</td>
<td>318.53</td>
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<td>4.7558</td>
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<td>51.447</td>
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<td>3.1672</td>
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<td>60.965</td>
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<td>717.81</td>
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<td>2.5125</td>
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<td>61.405</td>
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<td>1.3483</td>
<td>2.5041</td>
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</tr>
</tbody>
</table>

3-Stage Radial (Mixed Flow) Compressor

Meets Target Efficiency

3-Stage Overall Efficiency

From General Electric Site
BCL Series Compressor

Barber Nichols

Large System
Large Density Variation for Main Compressor Makes for a Difficult Design

CO2 Pressure-Density from NIST

Need to Keep Compressor Inlet Density In Small Range for Successful Operation

Large System
Main Compressor
Radial Type

- Close to the Dome During Startup/Shutdown/System Upset/Wet Gas Handling
- Radial Head/Flow Characteristics for Startup/Shutdown Flow/Pressure Transients
- Flat Head v Flow Characteristic Allows Maintenance of Head over a Wider Flow Range
- Reduced Number of Stage for Overhung Configuration (Rotordynamic Consideration)
- Shrouded Design for Best Efficiency
## Re-Compressor Axial Type

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tr>
<td>Pressure Ratio</td>
<td>1.226</td>
<td>1.2033</td>
<td>1.18</td>
<td>1.146</td>
<td>1.1126</td>
<td>1.0914</td>
<td>1.0711</td>
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<tr>
<td>P in psia</td>
<td>1116</td>
<td>1369</td>
<td>1647</td>
<td>1945</td>
<td>2228</td>
<td>2480</td>
<td>206</td>
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<tr>
<td>P out psia</td>
<td>1369</td>
<td>1647</td>
<td>1945</td>
<td>2228</td>
<td>2480</td>
<td>2706</td>
<td>2899</td>
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<tr>
<td>Specific Speed</td>
<td>144</td>
<td>138</td>
<td>134</td>
<td>141</td>
<td>157</td>
<td>171</td>
<td>194</td>
</tr>
<tr>
<td>D tip (inches)</td>
<td>42</td>
<td>40.7</td>
<td>39.5</td>
<td>38.3</td>
<td>37.1</td>
<td>35.8</td>
<td>34.6</td>
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<tr>
<td>D hub (inches)</td>
<td>39.1</td>
<td>37.8</td>
<td>36.7</td>
<td>35.5</td>
<td>34.4</td>
<td>33.2</td>
<td>32</td>
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<tr>
<td>Hub/Tip Ratio</td>
<td>0.930952</td>
<td>0.928747</td>
<td>0.929114</td>
<td>0.926893</td>
<td>0.927224</td>
<td>0.927374</td>
<td>0.924855</td>
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</tbody>
</table>

Hub/Tip Ratio is Above .9 (Needs Further Review)

**Barber Nichols**

*Large System*
Analysis Was Done For Multi-Stage Radial Compressors

Re-Compressor as Radial 84%

Difficult to Obtain High Efficiency

<table>
<thead>
<tr>
<th>Three Stage Temperature (°F)</th>
<th>Temperature Pressure (psia)</th>
<th>Temperature Density (lbm/ft³)</th>
<th>Enthalpy (Btu/lbm)</th>
<th>Entropy (Btu/lbm-°R)</th>
<th>Cp (Btu/lbm-°R)</th>
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<tbody>
<tr>
<td>157.26</td>
<td>1116.5</td>
<td>10.281</td>
<td>205.95</td>
<td>0.45305</td>
<td>0.38367</td>
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<tr>
<td>220.03</td>
<td>1675</td>
<td>13.848</td>
<td>214.55</td>
<td>0.45305</td>
<td>0.38935</td>
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<td>223.98</td>
<td>1675</td>
<td>13.631</td>
<td>216.07</td>
<td>0.45528</td>
<td>0.3827</td>
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<td>273.68</td>
<td>2275</td>
<td>16.834</td>
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<tr>
<td>277.07</td>
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<td>16.641</td>
<td>224.66</td>
<td>0.45704</td>
<td>0.3789</td>
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<tr>
<td>317.58</td>
<td>2900</td>
<td>19.46</td>
<td>231.07</td>
<td>0.45704</td>
<td>0.37647</td>
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<td>320.58</td>
<td>2900</td>
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<td>0.45849</td>
<td>0.37382</td>
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<td>309.46</td>
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<td>19.941</td>
<td>227.99</td>
<td>0.45305</td>
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Wheel Diameter Inches

Large System
**Ns-Ds Diagram Turbines (English Units)**

Axial Turbine Highest Efficiency
Speed and Diameter

Large System
# Turbine Design (3-Stage Axial)

## 90% Efficiency

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### Axial Reaction Turbine Summary

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turb In Temp F</td>
<td>1022</td>
<td>955</td>
<td>888</td>
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<tr>
<td>Nozz In Temp F</td>
<td>972</td>
<td>905</td>
<td>839</td>
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<tr>
<td>Rotor Out Temp F</td>
<td>951</td>
<td>883</td>
<td>819</td>
</tr>
<tr>
<td>Turb Out Temp F</td>
<td>955</td>
<td>888</td>
<td>823</td>
</tr>
<tr>
<td>Mass Flow lb/sec</td>
<td>7683</td>
<td>7683</td>
<td>7683</td>
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<tr>
<td>Adiab. Head B/#</td>
<td>19.735</td>
<td>19.735</td>
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<td>Hub Dia 1 Inch</td>
<td>28.59</td>
<td>36.43</td>
<td>32.14</td>
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<tr>
<td>Hub Dia 2 Inch</td>
<td>32.23</td>
<td>38.64</td>
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<tr>
<td>Tip Diameter Inch</td>
<td>45.687</td>
<td>47.58</td>
<td>48.9</td>
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<td>Reaction</td>
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<td>0.4</td>
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<tr>
<td>Blade Chord Inch</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
<td># Blades</td>
<td>85</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Specific Speed</td>
<td>93</td>
<td>105</td>
<td>125</td>
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</tbody>
</table>

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Large System
Turbine (Single Stage Radial)
90% Efficiency ~1.9 meter Diameter

Specific Speed .41 Shows 90%+
Efficiency T-S

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Pressure (MPa)</th>
<th>Density (kg/m³)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (kJ/kg-K)</th>
<th>Cp</th>
<th>Cp/Cv</th>
<th>delH Isentropic</th>
<th>Ns</th>
<th>Optimum U/Co</th>
<th>Utip m/s</th>
<th>Diameter Rotor m</th>
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<tr>
<td>550</td>
<td>19.83</td>
<td>123.38</td>
<td>1035.3</td>
<td>2.7429</td>
<td>1.2404</td>
<td>1.2412</td>
<td>134.28</td>
<td>0.41</td>
<td>53.42</td>
<td>0.69</td>
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<td>428.8</td>
<td>7.9</td>
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<td>2.7429</td>
<td>1.1677</td>
<td>1.2351</td>
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<tr>
<td>440.29</td>
<td>7.9</td>
<td>58.491</td>
<td>914.45</td>
<td>2.7619</td>
<td>1.1712</td>
<td>1.2324</td>
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</tbody>
</table>

Radial Flow Turbine
3600RPM
Wdot 3485kg/s

Figure 17: Effect of specific speed on radial inflow turbine efficiency. (Replotted from Ref. 25.)

Large System
300 Mwe Super-Critical CO2 Closed Brayton Cycle Rotating Group

Axial Turbine

Liftoff Gas Seal

Main Compressor

Hydrodynamic Bearing

Oil Lubed

Axial Re-compressor

Thrust/Radial Bearing

Labyrinth Seal

Labyrinth Seal

300 Mwe Generator Rotor

To Scale

~10 meters + spool + 12 meters

Overall Length ~ 22 meters

Large System
Large Scale System

Oil Lubricated Hydrodynamic Bearings

-Thrust and Journal Hydrodynamic Bearings (Industry Standard for Power Generation Equipment, Waukesha)
Liftoff Gas Seal (John Crane)
Surface Speeds/Pressures/Temperatures/CO2 Currently Offered

**Typical Double Opposed Seal Arrangement and Seal Support System**

*Double Seal Arrangement where hazardous gas is not permissible to leak into atmosphere.*

Dry Gas Seal Machinery Necessary
Require Monitoring
Storage, Compression
Re-Introduction
(From GE Site)

Barber Nichols

Large System
Small Scale System ~300 kWe

- Study SCO2 Closed Brayton Cycle on Small/Affordable Scale
- Same Pressures and Much Lower Flow Rate
  - Higher Speed Machinery to Gain Efficiency
  - Radial Compressors and Turbine
  - High Speed PM Motor/Generator
  - Bearings/Seals for Large System Not Optimum for Small System
### Small Scale Loop (Mass Flow 5 kg/s)

<table>
<thead>
<tr>
<th>Station</th>
<th>T (K)</th>
<th>P (Mpa)</th>
<th>mdot (kg/s)</th>
<th>eff</th>
<th>(dP/P)</th>
<th>kJ/kg</th>
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<tbody>
<tr>
<td>1</td>
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<td>3</td>
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<td>72</td>
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<td>2</td>
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<td></td>
<td>68</td>
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<td>3</td>
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<td>4</td>
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<td>5</td>
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<td>6</td>
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<td>5</td>
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<td>0.01</td>
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<td>8</td>
<td>375</td>
<td>7.77</td>
<td>3</td>
<td></td>
<td>85</td>
<td>0.01</td>
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</table>
**Cycle Analysis with Pressure Drops**

\(~279\) kWe Net Electric Power

<table>
<thead>
<tr>
<th>Component</th>
<th>(P_1) (Mpa)</th>
<th>(P_2) (Mpa)</th>
<th>(H_1)</th>
<th>(H'_2)</th>
<th>(\text{eff})</th>
<th>(H_2)</th>
<th>(\text{mdot})</th>
<th>Power (kW)</th>
<th>Speed (rpm)</th>
<th>(\text{psi})</th>
<th>(D_2) (inches)</th>
<th>(Ns)</th>
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<tr>
<td>Radial Main</td>
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<td>19.9</td>
<td>524.1</td>
<td>585.4</td>
<td>0.68</td>
<td>614.3</td>
<td>3</td>
<td>180.4</td>
<td>80,000</td>
<td>0.58</td>
<td>3.06</td>
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<td>Radial Re-Comp</td>
<td>7.77</td>
<td>19.9</td>
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<td>585.4</td>
<td>0.68</td>
<td>614.3</td>
<td>5</td>
<td>566</td>
<td>80,000</td>
<td>0.65</td>
<td>3.06</td>
<td>33.8</td>
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<tr>
<td>Radial Turbine</td>
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<td>924.4</td>
<td>3</td>
<td>75.6</td>
<td>80,000</td>
<td>0.58</td>
<td>1.66</td>
<td>45.5</td>
</tr>
</tbody>
</table>

Net Shaft: 310
Net Elect: 279.93

- **High Temp Recuperator**
  - \(T\): 471 K, 505 K
  - \(Q\): 668 K

- **Low Temp Recuperator**
  - \(T\): 335 K, 375 K
  - \(Q\): 462 K @3 kg/s

**Cycle Efficiency is .32**
*Before Electrical and Mechanical Parasitic Losses*

*Small Scale System*
Oil Lubricated Bearings with Seals to Use “Large Machine” Technology

Scaled Loop Machinery (2 bearing option)

Liftoff Gas Seal

Alternator

Exhaust

Bearing

Labyrinth Seal

Bearing

+Thrust Loads Balanced
~Flexible Rotor vs Liftoff Seal Runout?
Detailed Design Necessary

Small Scale System
Oil Lubricated Bearings with Seals to Use “Large Machine” Technology

Scaled Loop Machinery
(4 bearing option, more seals)

Liftoff Gas Seal

Alternator

Bearing 4 Places

Exhaust

Liftoff Gas Seals

Quill Shaft

Small Scale System
Oil Lubricated Bearings with Seals to Use “Large Machine” Technology

Scaled Loop Machinery
(2 Shaft Option)

Oil Lube Bearing 2 Places

Exhaust

Liftoff Gas Seal

Small Scale System
Simplified Design

• CO2 Bearing Supply
  – Hydrostatic
  – Hydrodynamic
    • Flex Pad
    • Foil

• Generator Operating in CO2
  – Eliminate Gas Liftoff Seals/Laby Seals OK
  – Supercritical CO2 Degradation of Insulation
  – Windage Loss
Generator Technology
Very High Power/Speed
Compact for Rotordynamics

Permanent Magnet Generator
-45 MGOe NIB Magnet
-Aron 5 Laminations
-7” Stack Length
-5” Outer Diameter
-Inconel 718 Rotor Can
-279 kWe Output at 80,000 rpm
-98% Efficiency

-Windage in CO2 at 170 deg F
-62 kW @ 1100 psi
-11 kW @ 250 psi
-1 kW @ 14.7 psi

Need to Operate Generator at Low Pressure
Main Compressor Analysis

*Looks More Like a Pump Than a Compressor*

- Developed Defined Procedure
- Use Real Gas Mean Line Code
- Modify for Ideal Gas
  - Flow Path Analysis
  - Sizing
  - Input to CFD Code with Average CO2 Properties

*Small Scale System*
Other Considerations To Be Considered When Designing Turbomachinery

- Rotordynamics
- Thrust Load Management
- Startup/Shutdown Transients
- Clearances
- Inlet/Discharge Diffusion etc.
- Stresses (Including Thermal/Fatigue/Operating etc)