Study of a Supercritical CO$_2$ Turbine with TIT of 1350 K for Brayton Cycle with 100 MW Class Output: Aerodynamic Analysis of Stage 1 Vane

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Presented at
The 4th International Symposium - Supercritical CO2 Power Cycles
September 10, 2014, Pittsburgh, Pennsylvania
Outline

• Introduction
• Cycle Diagram
• Mean-line design
• Aerodynamic loss estimation
• First stage airfoil modeling
• Real fluid property CFD
• Results
• Conclusions
Introduction

• $\text{SCO}_2$ technology may provide an economic alternative to current technologies
• Brayton cycle chosen
• Heat added through exchangers and/or oxy-fuel combustion
• This study chooses a 100 MW net power output
• Operates at 3600 RPM to facilitate grid connection
Cycle P-T Diagram

- \( \text{CO}_2 \) properties from REFPROP
- Recuperated cycle provides highest efficiency for low pressure ratios
- Cycle operates entirely in the supercritical region
- Temperature at the turbine inlet chosen to be 1350 K
- Compressor pressure ratio of approximately 4:1

Pressure vs temperature cycle diagram
First Stage 1D Mean-line Design

- Constant radius mean-line
- Flow velocity enters axially
- Entrance Mach number kept below 0.3
- 6 stage turbine found to have the best per-stage loading coefficient
- Flow coefficient is chosen using Smith Chart to maximize efficiency

Aerodynamic design
Smith Chart
(Horlock, 1966)
First Stage 1D Mean-line Design – Loss Estimation

• Soderberg’s equation provides a parameter for estimating loss

\[ \zeta = 0.04 \left[ 1 + 1.5 \left( \frac{\varepsilon}{100} \right)^2 \right] \]

• Total-to-total and total-to-static efficiencies can be estimated from this parameter

\[ \eta_{TT} = \left[ 1 + \varphi \frac{\zeta_R / \cos^2 \beta_3 + \zeta_N / \cos^2 \alpha_2}{2 \tan \alpha_2} \right]^{-1} \]

\[ \eta_{TS} = \left[ 1 + \varphi \frac{\zeta_R / \cos^2 \beta_3 + \zeta_N / \cos^2 \alpha_2 + 1}{2 \tan \alpha_2} \right]^{-1} \]

Soderberg’s equations for loss estimation
(Horlock, 1966)
An initial mean-line reaction of 0.5 is selected.

Reaction is adjusted to give angles with the lowest aerodynamic losses.

Soderberg’s relation provides simple basis for initial loss estimation.

Optimized triangles resulted in slightly reduced mean-line reaction.

First stage mean-line velocity triangles
First Stage Airfoil Design

Design parameters at mean, hub, and casing

<table>
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<tr>
<th></th>
<th>Mean</th>
<th>Hub</th>
<th>Casing</th>
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<tbody>
<tr>
<td>(\varphi)</td>
<td>0.514</td>
<td>0.529</td>
<td>0.500</td>
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<tr>
<td>(\alpha_2(\text{o}))</td>
<td>70.7</td>
<td>71.2</td>
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<td>(\alpha_3(\text{o}))</td>
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<td>5.9</td>
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<tr>
<td>(\beta_2(\text{o}))</td>
<td>42.3</td>
<td>46.5</td>
<td>37.7</td>
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<tr>
<td>(\beta_3(\text{o}))</td>
<td>63.9</td>
<td>63.3</td>
<td>64.5</td>
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<tr>
<td>(\epsilon_N(\text{o}))</td>
<td>70.7</td>
<td>71.2</td>
<td>70.2</td>
</tr>
<tr>
<td>(\epsilon_R(\text{o}))</td>
<td>106.3</td>
<td>109.8</td>
<td>102.3</td>
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<tr>
<td>(R)</td>
<td>0.292</td>
<td>0.249</td>
<td>0.331</td>
</tr>
<tr>
<td>(\zeta_N)</td>
<td>0.070</td>
<td>0.070</td>
<td>0.070</td>
</tr>
<tr>
<td>(\zeta_R)</td>
<td>0.108</td>
<td>0.112</td>
<td>0.103</td>
</tr>
<tr>
<td>(\eta_{TT}(%))</td>
<td>0.903</td>
<td>0.900</td>
<td>0.905</td>
</tr>
<tr>
<td>(\eta_{TS}(%))</td>
<td>0.835</td>
<td>0.832</td>
<td>0.837</td>
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</tbody>
</table>

- Free vortex selection gives tangential flow velocities at hub and casing (satisfies radial equilibrium)
- Triangles for hub and casing are determined
- Design optimization used to meet 90% targeted efficiency
- Mean line radius: 40.4 cm (15.9 in)
- Inlet height: 2.35 cm (.925 in)
Aspect Ratio and Pitch Selection

• Using the chart, aspect ratio of 1.0 is chosen

• Zweifel’s correlation is used to guide selection of optimum pitch

• Final number of airfoils based on optimum pitch and design of aerodynamic throat passage

• The centroid of each cross section stacked radially.

Selection of optimum aspect ratio based on airfoil dimensions (Ainley and Mathieson, 1967)
First Stage Solid Modelling – Vane

- Modeled in Solidworks
- Designed to allow for individual airfoil replacement
- 138 airfoils in stationary ring
- Basic convective or advanced cooling applicable
First Stage Solid Modelling – Blade

- Modeled in Solidworks
- Designed to allow for individual airfoil replacement
- Future designs might include shrouded blades

- 132 airfoils in rotating section
- Blades connect to a disk via a “fir tree” root
- Basic convective or advanced cooling applicable
Real Fluid CFD – Vane Mesh

- With current design vane losses have 30% more effect over blade losses on stage efficiency
- CFD of stationary section performed with STAR-CCM+
- 2.5M Polyhedral cells
- 15 body-fitted prism layers 0.2 mm thick with first cell thickness of 2.5e-6 cm
- Mesh extended by 1.5 cm axially at inlet and exit to capture all potential flow effects
Real Fluid CFD – CO₂ Properties

- CO₂ property behavior input as tables from REFPROP
- Properties vary greatly in the compressor, but not in the turbine
- For range of CFD modelled pressures, property variation was 1% or less
- Specific heat and viscosity input as functions of temperature only
- Turbulence set to k-epsilon with 20% intensity

Property variation of CO₂ specific heat and viscosity near the critical point
• Using inlet conditions and outlet static pressure, mass flow is converged on
• Metal boundaries are adiabatic
• Adiabatic conditions chosen for wall
• Adiabatic results provide the most optimistic estimation of aerodynamic losses
• Periodic boundary on flow path sides
Adiabatic Vane Results – Flow Velocity

- Areas of stagnant velocity at the leading and trailing edge
- Highest velocity at the throat
- Mass average velocity magnitude: 243.5 m/s, 10.8% lower than design
- Mass average velocity exit angle: $71.2^\circ$, 0.71% higher than design
- CFD successfully modelled the flow turning and accelerating to near expected parameters

Flow velocity at the mean-line through first stage vane
Total Pressure Variation at the Exit

- Pressure at the exit of the vane in an annular slice
- Turbulence and boundary layer are in areas of low total pressure
- Areas of low pressure indicate areas of loss and should be reduced
- Design adjustments are needed to minimize loss further

Total Pressure at vane exit in r-θ plane.
Adiabatic Vane Results – Temperature Variation

- Surface temperature variation of the airfoil
- Useful for designing appropriate cooling for high temperature conditions
- Higher temperature on the pressure side, lower on the suction side
- Stagnant air at trailing edge creates local hot zone
CFD Results and Loss Comparison

Mass flow averaged CFD results

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<tr>
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<th>inlet</th>
<th>exit</th>
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</thead>
<tbody>
<tr>
<td>Total Pressure (MPa)</td>
<td>28.43</td>
<td>28.20</td>
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<tr>
<td>Static Pressure (MPa)</td>
<td>28.13</td>
<td>25.69</td>
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<tr>
<td>Total Temperature (K)</td>
<td>1350.0</td>
<td>1350.0</td>
</tr>
<tr>
<td>Static Temperature (K)</td>
<td>1347.9</td>
<td>1332.2</td>
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<tr>
<td>Total Enthalpy (kJ/kg)</td>
<td>1713.6</td>
<td>1713.6</td>
</tr>
<tr>
<td>Static Enthalpy (kJ/kg)</td>
<td>1710.5</td>
<td>1689.6</td>
</tr>
<tr>
<td>Velocity Magnitude (m/s)</td>
<td>78.4</td>
<td>217.2</td>
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<tr>
<td>Flow Angle (°)</td>
<td>0</td>
<td>71.2</td>
</tr>
</tbody>
</table>

Soderberg vs CFD loss and efficiency

<table>
<thead>
<tr>
<th></th>
<th>Soderberg</th>
<th>CFD</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Pressure Loss (MPa)</td>
<td>0.125</td>
<td>0.230</td>
<td>0.105</td>
</tr>
<tr>
<td>Static Enthalpy Drop (kJ/kg)</td>
<td>19.68</td>
<td>20.90</td>
<td>1.22</td>
</tr>
<tr>
<td>Total-to-total Efficiency (%)</td>
<td>90.3</td>
<td>85.7</td>
<td>-4.6</td>
</tr>
<tr>
<td>Total-to-static Efficiency (%)</td>
<td>83.5</td>
<td>79.2</td>
<td>-4.3</td>
</tr>
</tbody>
</table>

- Correct mass flow rate converged on by STAR-CCM+
- Higher losses from CFD than simple traditional methods
Suggestions for Performance Improvement

- Further shape optimization is necessary to achieve design efficiency
- Larger sized turbines might allow for fewer losses
  - Longer airfoils reduce end/wall losses
  - Fewer blades to match Zweifel’s suggested pitch
- Investigation of loss corrections to the Soderberg method
Conclusions and Path Forward

• Real fluid behavior can be modeled with a mean-line design approach as a starting point

• CFD models the real fluid behavior of SCO$_2$, including the acceleration, direction, pressure and temperature

• CFD predicts a larger drop in pressure and enthalpy than initial, simple Soderberg estimations

• Model can be validated with laboratory tests

• Optimization of the cascade to improve efficiency
References


Questions?

Center for Advanced Turbomachinery and Energy Research

Aerodynamics & Heat Transfer

Combustion & Emissions

Alternative Fuels

Cycle Innovation

Extreme Temp Materials

CATER
9 faculty members, 50 Graduate & 40 UG students

Design & Manufacturing

Polymer/Ceramic Composites

Dynamic Integrity

Mechanical Integrity

Plant & Grid Transients

ing to the energy needs of society
Variation at the Exit with Increasing Radius

- Total pressure and temperatures are near expected values
- Static values increase with increasing radius indicating decreasing velocity

- Velocity behavior at exit indicates free vortex conditions
- Free vortex conditions are achieved in the CFD simulation