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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Outline

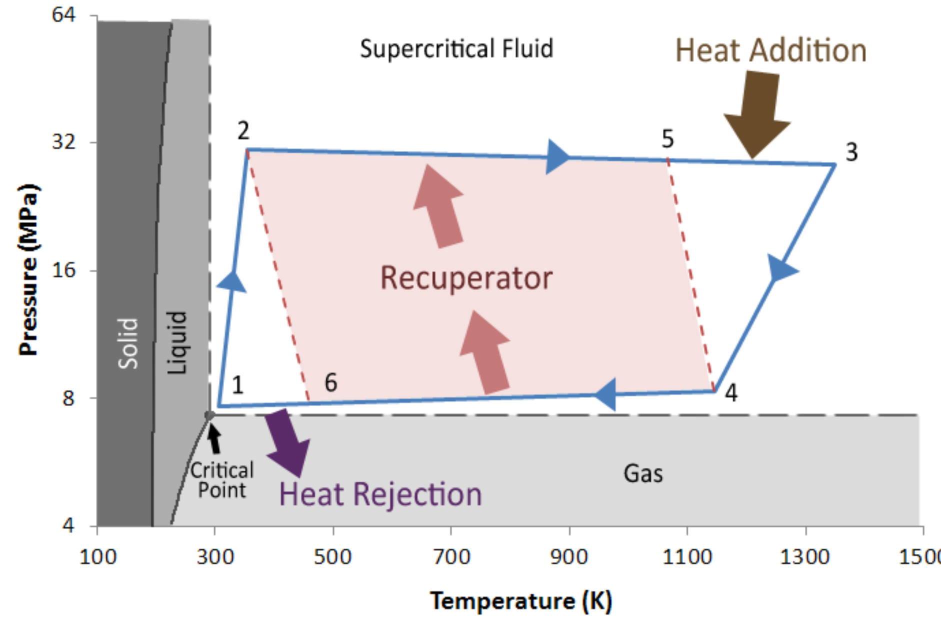
- Introduction
- Cycle Diagram
- Mean-line design
- Aerodynamic loss estimation
- First stage airfoil modeling
- Real fluid property CFD
- Results
- Conclusions

Introduction

- 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

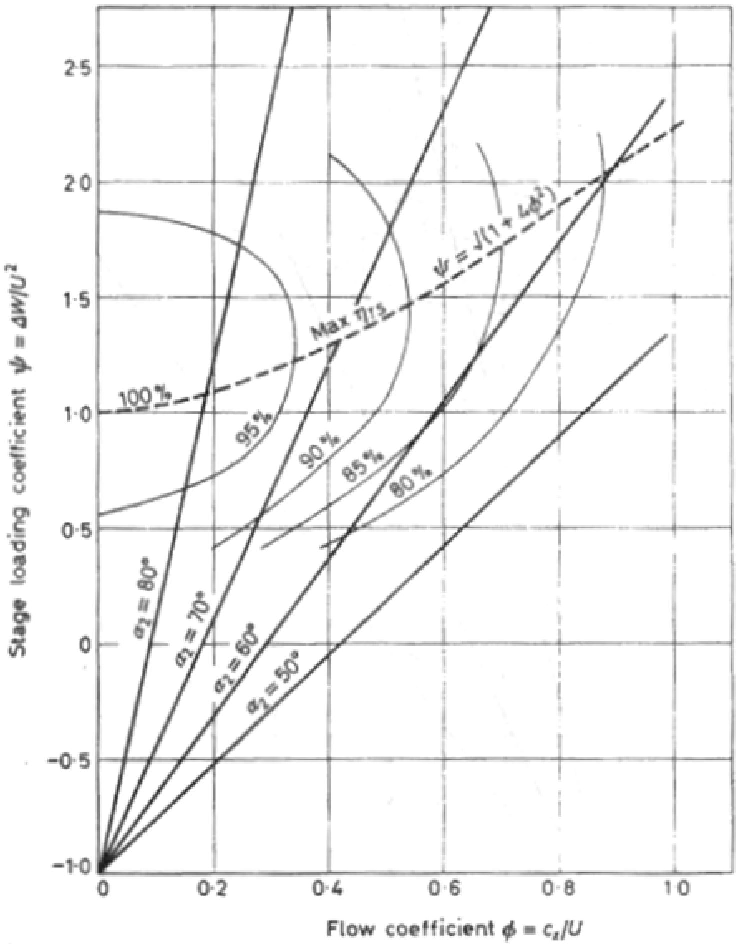
- CO_2 properties from REFPROP
- Recuperated cycle provides highest efficiency for low pressure ratios
- Cycle operates entirely in the supercritical region
- Temperature at the turbine inlet chosen to be 1350 K
- Compressor pressure ratio of approximately 4:1



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
- Total-to-total and total-to-static efficiencies can be estimated from this parameter
- Initial design uses this correlation for targeting maximum efficiency

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

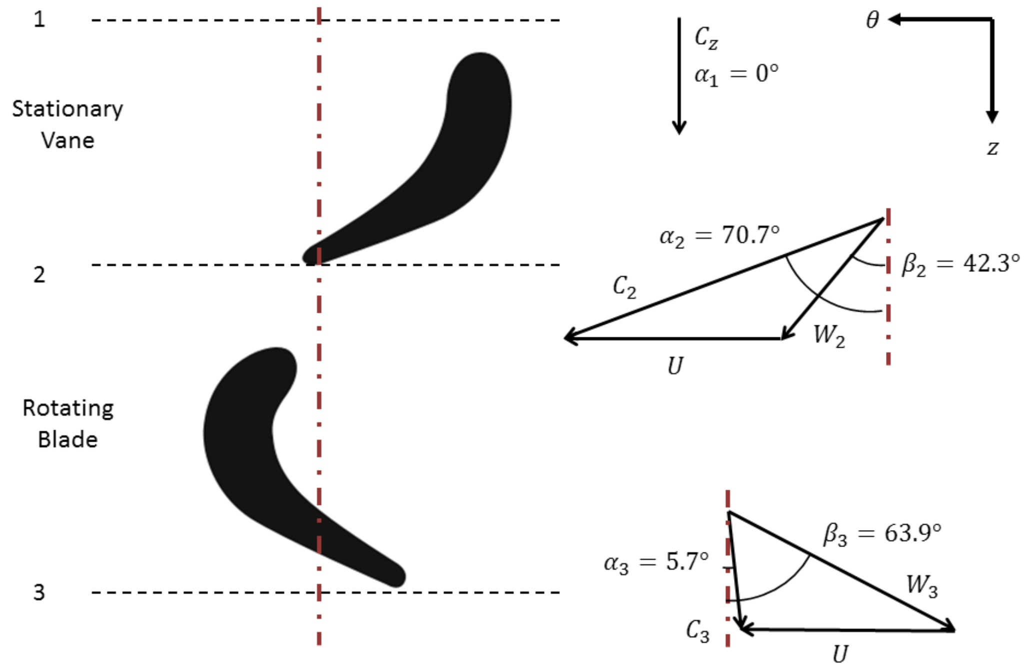
$$\eta_{TT} = \left[1 + \varphi\,\frac{\zeta_R/\cos^2\beta_3 + \zeta_N/\cos^2\alpha_2}{2\ \tan\alpha_2}\right]^{-1}$$

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

Soderberg's equations for loss estimation (Horlock, 1966)

1D Mean-line Design – Velocity Triangles

- 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

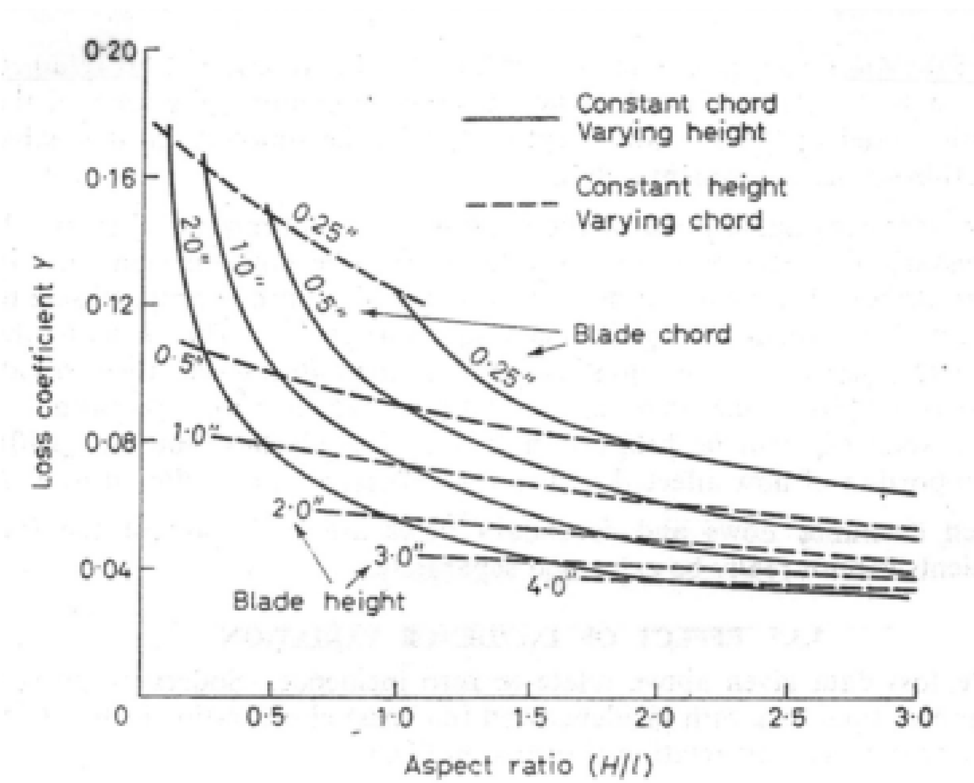
- Free vortex selection gives tangential flow velocities at hub and casing (satisfies radial equillibrium)
- Triangles for hub and casing are determined
- Design optimization used to meet 90% targeted efficiency
- Mean line radius: 40.4 cm (15.9 in)
- Inlet height: 2.35 cm (.925 in)

Design parameters at mean, hub, and casing

	Mean	Hub	Casing
φ	0.514	0.529	0.500
α_2(º)	70.7	71.2	70.2
α_3(º)	5.7	5.9	5.6
β_2(º)	42.3	46.5	37.7
β_3(º)	63.9	63.3	64.5
ϵ_N(º)	70.7	71.2	70.2
ϵ_R(º)	106.3	109.8	102.3
R	0.292	0.249	0.331
ζ_N	0.070	0.070	0.070
ζ_R	0.108	0.112	0.103
η_{TT}(%)	0.903	0.900	0.905
η_{TS}(%)	0.835	0.832	0.837

Aspect Ratio and Pitch Selection

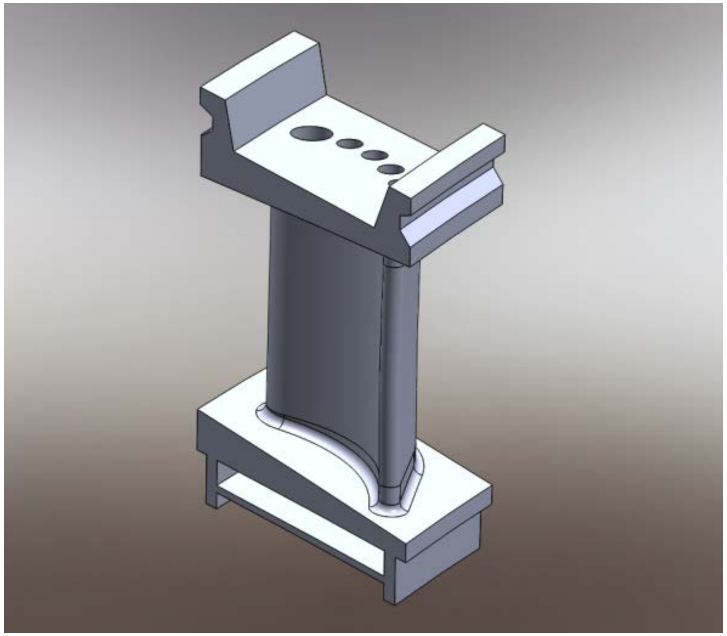
- Using the chart, aspect ratio of 1.0 is chosen
- Zweifel's correlation is used to guide selection of optimum pitch
- Final number of airfoils based on optimum pitch and design of aerodynamic throat passage
- The centroid of each cross section stacked radially.



Selection of optimum aspect ratio based on airfoil dimensions (Ainley and Mathieson, 1967)

First Stage Solid Modelling – Vane

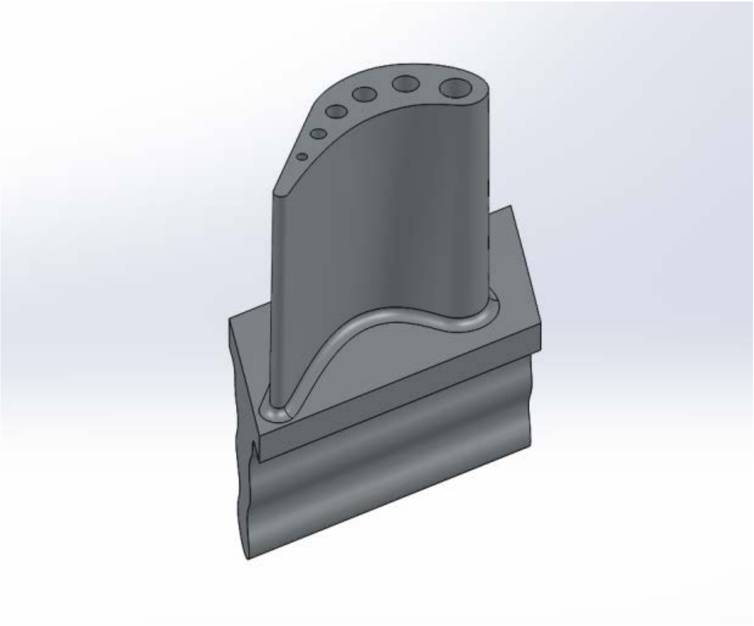
- Modeled in Solidworks
- Designed to allow for individual airfoil replacement

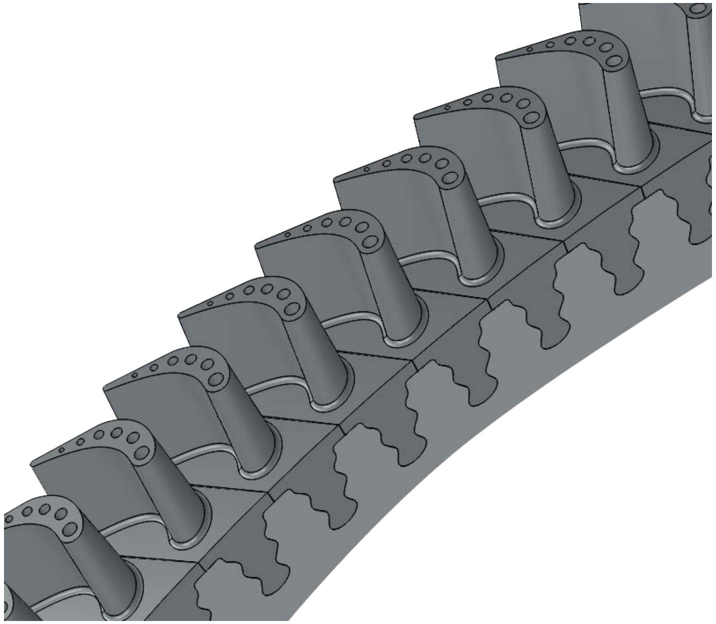


- 138 airfoils in stationary ring
- Basic convective or advanced cooling applicable

First Stage Solid Modelling – Blade

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

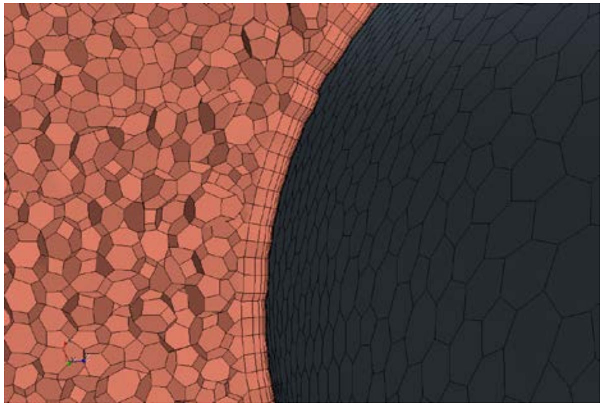




- 132 airfoils in rotating section
- Blades connect to a disk via a “fir tree” root
- Basic convective or advanced cooling applicable

Real Fluid CFD – Vane Mesh

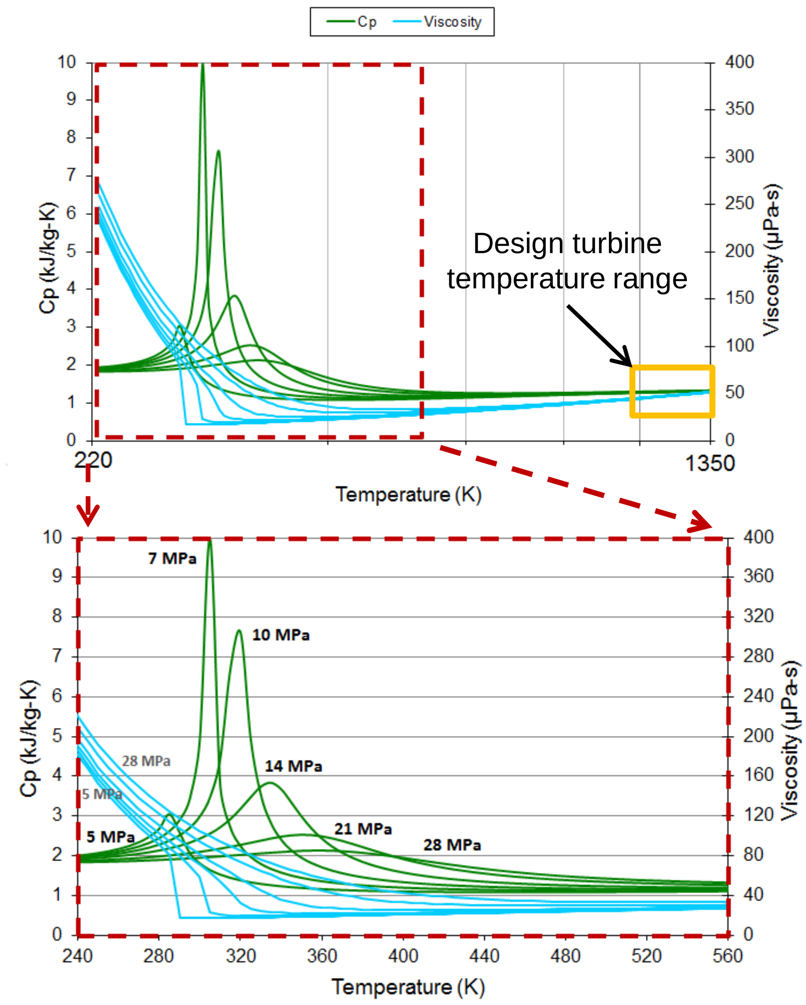
- With current design vane losses have 30% more effect over blade losses on stage efficiency
- CFD of stationary section performed with STAR-CCM+
- 2.5M Polyhedral cells
- 15 body-fitted prism layers 0.2 mm thick with first cell thickness of 2.5e-6 cm
- Mesh extended by 1.5 cm axially at inlet and exit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



Vane flow path CFD mesh

Real Fluid CFD – CO_2 Properties

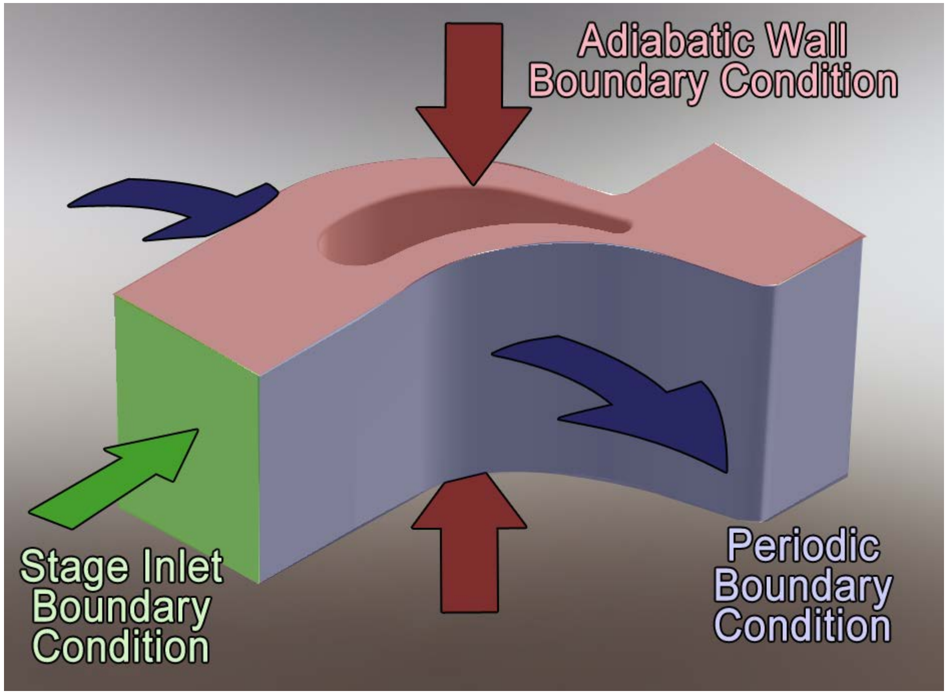
- CO_2 property behavior input as tables from REFPROP
- Properties vary greatly in the compressor, but not in the turbine
- For range of CFD modelled pressures, property variation was 1% or less
- Specific heat and viscosity input as functions of temperature only
- Turbulence set to k-epsilon with 20% intensity



Property variation of CO_2 specific heat and viscosity near the critical point

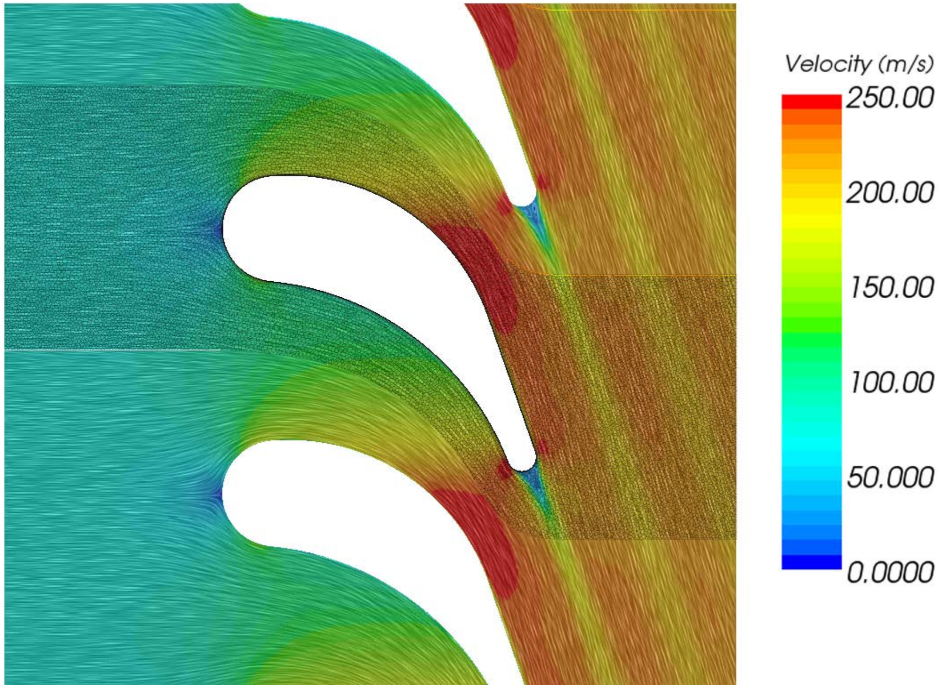
Real Fluid CFD – Boundary Conditions

- 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

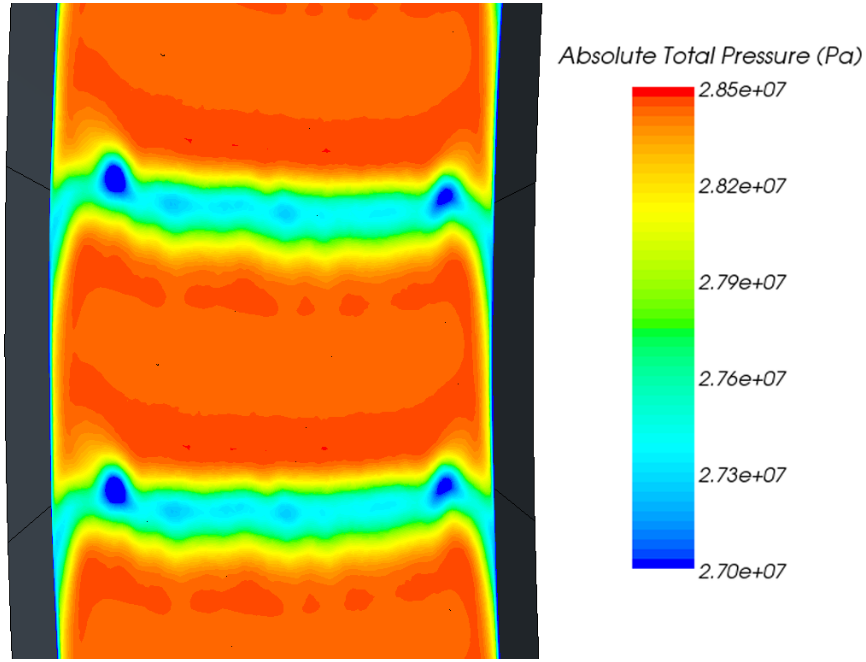
- Areas of stagnant velocity at the leading and trailing edge
- Highest velocity at the throat
- Mass average velocity magnitude: 243.5 m/s, 10.8% lower than design
- Mass average velocity exit angle: 71.2° , 0.71% higher than design
- CFD successfully modelled the flow turning and accelerating to near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



Flow velocity at the mean-line through first stage vane

Total Pressure Variation at the Exit

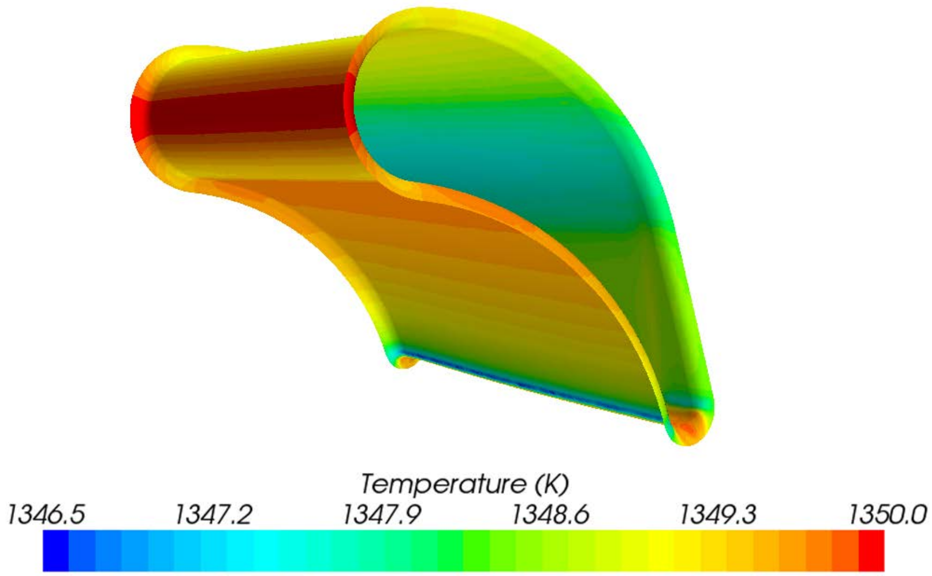
- Pressure at the exit of the vane in an annular slice
- Turbulence and boundary layer are in areas of low total pressure
- Areas of low pressure indicate areas of loss and should be reduced
- Design adjustments are needed to minimize loss further



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



Adiabatic vane airfoil surface temperature distribution

CFD Results and Loss Comparison

Mass flow averaged CFD results

	inlet	exit
Total Pressure (MPa)	28.43	28.20
Static Pressure (MPa)	28.13	25.69
Total Temperature (K)	1350.0	1350.0
Static Temperature (K)	1347.9	1332.2
Total Enthalpy (kJ/kg)	1713.6	1713.6
Static Enthalpy (kJ/kg)	1710.5	1689.6
Velocity Magnitude (m/s)	78.4	217.2
Flow Angle (º)	0	71.2

Soderberg vs CFD loss and efficiency

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

- 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

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- Horlock, J.H, University of Cambridge, “Axial Flow Turbines”, Butterworth and Co., 1966.
- Ainley, D. G., and Mathieson, G. C. R., “A Method of Performance Esitmation for Axial Flow Turbines”, London, 1967.

Questions?

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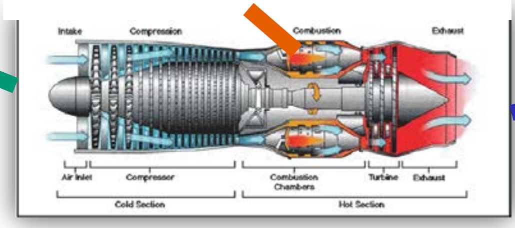


Aerodynamics & Heat Transfer

Combustion & Emissions

Alternative Fuels

Cycle Innovation

Extreme Temp Materials

CATER

9 faculty members, 50 Graduate & 40 UG students

Mechanical Integrity

Design & Manufacturing

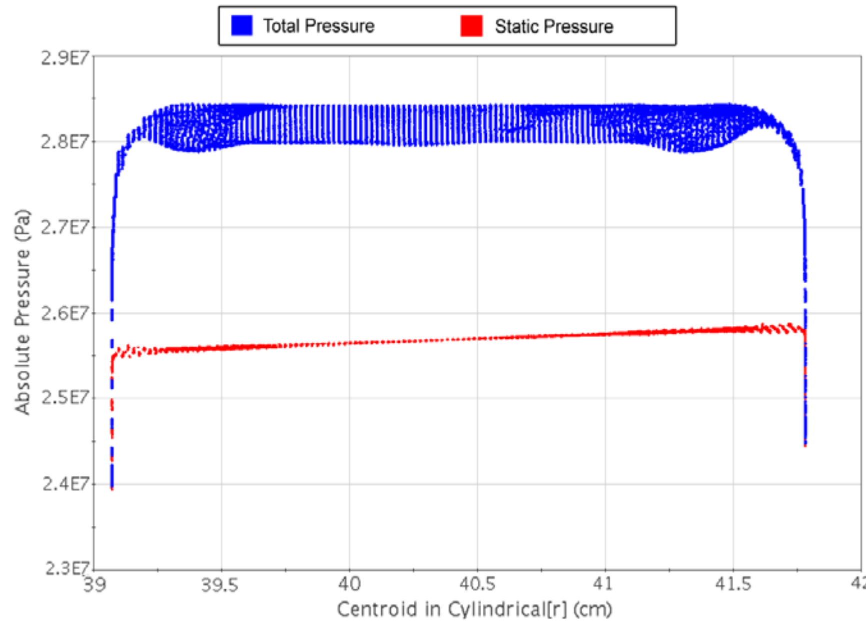
Polymer/Ceramic Composites

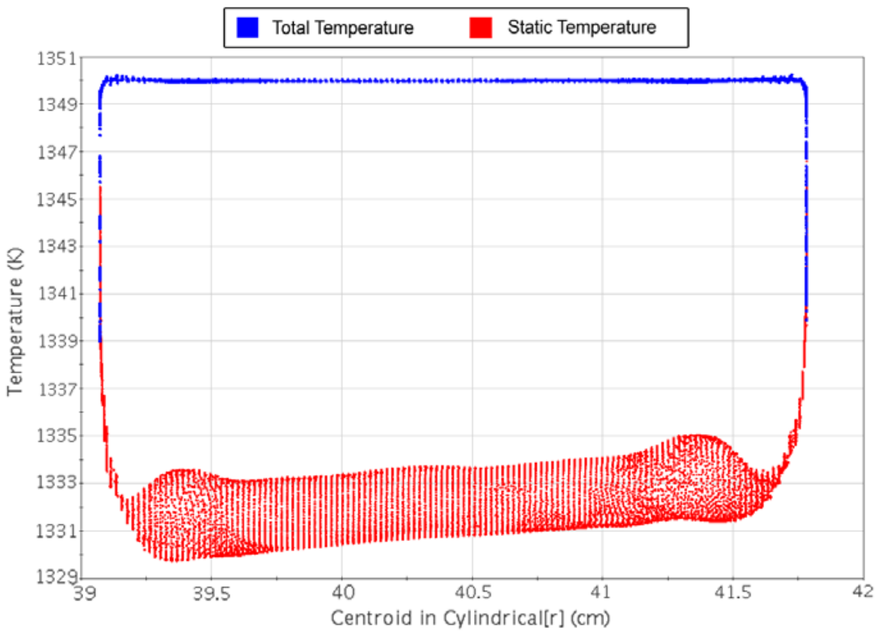
Dynamic Integrity

Plant & Grid Transients

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