Low-leakage seals for utility-scale sCO\textsubscript{2} turbines

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Outline

• Value of face seals – utility-scale sCO₂ turbines

• Face Seal Concept

• Analyses of Face Seal
  • Fluid Analyses
    • Reynolds equation model
    • 3D CFD model
  • Mechanical Analysis
  • Thermal Analysis

• Progress overview & Next steps
sCO₂ Application Space

- Direct Fired sCO₂ 2030+
- sCO₂ Fossil 2025+
- Gen 4 Nuclear 2030+
- Steam
- HDGT CC
- LWR

- sCO₂ CSP 50+ % $\eta_{th}$ 2020-2025
- sCO₂ WHR Compact $\eta_{th} >$ ORC 2015-2020
- ORC

Power Output [MWe]

Source Temperature [°C]

(From Hofer, 2014)
Layout of End Seals in sCO\textsubscript{2} turbines

450 MW\textsubscript{e} cycle – 51.9% efficient cycle

End Seal layout for a sCO\textsubscript{2} turbine

- End seals needed for shielding bearings from high-temp exhaust
- Turbine exhaust typically \(\sim1000\) psi pressure
- Seal leakage to atmospheric pressure needs to be recompressed using a scavenge compressor

sCO\textsubscript{2} cycles are closed loop & seal leakage flow needs to be recompressed

(From Bidkar et. al, 2016)
Need for low-leakage face seals

End Seal layout for a sCO₂

• Leakage flow calculated for existing technology (labyrinth seals) and new technology (face seals)
• Multi-stage centrifugal compressor designed as a scavenge compressor
• Comparison of labyrinth seals and face seals shows a 0.55% points cycle benefit for face seals

Face seals are worth ~0.55% points cycle efficiency compared to labyrinth seals
Face Seals for utility-scale sCO₂ turbines

- Face seals needed for utility-scale sCO₂ turbines (24-inch diameter, 1000 psia pressure differential) not readily available
- Concept design explored using fluid, mechanical and thermal analyses
sCO₂ Face Seals – Fluid Analyses

Face seal concept geometry

Typical domain for flow analysis

Approach # 1: Reynolds equation

\[
\frac{\partial}{\partial r} \left( r \frac{\partial (ph^3)}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( ph^3 \frac{\partial P}{\partial \theta} \right) = 6 \omega r \frac{\partial (ph)}{\partial \theta}
\]

\[
\frac{dp}{p} = \frac{\gamma M^2}{1 - M^2} \left( \frac{dA}{A} \right) - \frac{\gamma M^2 [1 + (\gamma - 1) M^2]}{2(1 - M^2)} \left( \frac{4C_f dr}{D_h} \right)
\]

\[
\frac{dM}{M} = -\left[ 1 + 0.5 (\gamma - 1) M^2 \right] \left( \frac{dA}{A} \right) - \frac{\gamma M^2 [1 + 0.5 (\gamma - 1) M^2]}{2(1 - M^2)} \left( \frac{4C_f dr}{D_h} \right)
\]

Fluid analyses goal: Predict pressure on the bearing face, predict leakage & windage heat generation

Two approaches used for analyzing the fluid flow

- Approach # 1: Reynolds equation
- Approach # 2: ANSYS 3D CFD with CO₂ real gas properties

Compare the results and validity of the two approaches
sCO$_2$ Face Seals – Fluid Analyses

- Bearing pressure predictions match well for Approach # 1 (Reynolds equation) and Approach # 2 (ANSYS 3D CFX) for small film thickness.
- Increasing film thickness leads to turbulent flow and breakdown of Approach # 1 assumptions.
- sCO$_2$ films show larger heat generation (compared to air) due to higher density.

Higher density of sCO$_2$ needs turbulent flow modeling & full 3D modeling not possible with conventional 2D-1D models.
**sCO₂ Face Seals – Structural Analysis**

**Face seal concept geometry**

- Coning is the angular mismatch between the bearing face & the rotor
- Parametric Finite-element Model to analyze effect of geometry on coning sensitivity
- Isothermal FEM with pressure loads from the CFD model
- Increasing dimension ‘d’ leads to positive coning

**Parametric Finite Element Model used to explore the design space and optimize the seal cross-section for small positive coning**

**Coning for d = 0, a = 4, e 1.2**

**Coning for d = 2.5, a = 4, e 1.2**
sCO₂ Face Seals – Thermal Analysis

- Leakage flow, windage heat generation from CFD, and sCO₂ properties used as an input to the thermal model
- Heat transfer coefficients and thermal boundary conditions using local flow properties
- Advection model (energy conservation) used with ANSYS to predict metal temperatures
- Combined pressure-temperature loads used for predicting coning

Based on the fluid, structural & thermal analyses, a net pressure-thermal coning of about 0.0005 inches is possible
sCO$_2$ Seals Test Rig Concept

Full-scale test rig concept developed for face seal testing
sCO$_2$ Seals Rig Loop

Full-scale test rig to be coupled to existing CO$_2$ loop at Southwest Research
Progress Overview & Next Steps

Phase 1 Concept Design effort complete

- 50 MW_e and 450 MW_e Turbine layouts
- sCO_2 test rig Concept

Face seal concept
- 24-inch, 1100 psi

Phase 2 Detail design & testing to attain TRL6

- Concept Design TRL 2-3
- Subscale demo 5-inch face seal
- Design & fabrication of 24-inch face seals
- 24-inch sCO_2 rig design
- 24-inch sCO_2 rig commissioning
- Full-scale Testing
- Ready for Field Testing

Table: 2014-2019

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Summary and Conclusions

- Value of Face Seals
  - Face seals can enable a 0.55% points benefit over present labyrinth seals technology
- Unavailability of face seals for utility-scale sCO$_2$ turbines
- Face seal concept
  - Importance of 3D CFD with real gas properties
  - Coning analyses with pressure/thermal loads to show basic feasibility of the concept
- sCO2 Seals rig concept completed
- Plans for subscale & full-scale testing of seals
BACK-UP
Seal Concept

- Springs & pressure bias the stationary ring towards the rotor
- Spiral grooves generate separating force
- Seal tracks rotor axial transients
sCO\textsubscript{2} Seals test rig concept

Seal test rig concept developed for high pressure, high temperatures and large diameter seals