An Integrated Coupled-Physics Framework for Performance and Life Prediction of Supercritical CO2 Turbomachines

Azam Thatte, Lead Research Scientist - GE Global Research
Acknowledgements

* Work performed under U.S. DOE (EERE) PREDICTS program award # DE-EE0006345.

Co-authors:
Adrian Loghin, Etienne Martin, Voramon Dheeradhada, Youngwon Shin, Balajee Ananthasayanam

Partners:
Southwest Research Institute (Jeff Moore, Tim Allison)
Overview

- Award Number: DE-EE0006345
- PI: Azam Thatte (GE Global Research)
- Partner: Southwest Research Institute
- Project Budget: $2.41 Million (20% cost share by GE)
Problem Statement and Value Proposition

- Scalable Supercritical CO2 (sCO2) turbine expected to provide a major stepping stone for achieving CSP power at $0.06/kW-hr LCOE.
- Energy conversion efficiency > 50%, Total power block cost < $1,200/kW installed.
- Turbomachinery must have a 30-year life $\rightarrow$ ~ 11,000 thermal cycles.
- Under another Sunshot program (# DEEE0005804) GE and SWRI developing this 10MWe sCO2 turbine.
- Two key components critical to high efficiency of these sCO2 power cycles are:
  1. Hybrid gas bearing (HGB).
  2. Dry gas seal (DGS).

HGB $\rightarrow$ ~ 5% efficiency gain (rotordynamics & aero efficiency), avoids 500 KW parasitic losses.
HGB $\rightarrow$ Allows integral compressor $\rightarrow$ reduces cost.
DGS $\rightarrow$ ~ 10% improvement in efficiency (reduced leakage + generator windage)
DGS $\rightarrow$ No need of multi-stage intercooled compressor to recompress leakage.
10 MWe GE-SWRI Sunshot sCO2 Turbine

Instrumented Dry Gas Seal used for Model Validation
Why Hybrid Gas Bearing and Dry Gas Seal in sCO2 Turbines?

• **Hybrid Gas Bearing** → ~3% efficiency gain

• Rotordynamics → Needs mid-span support for high power densities.

• Oil bearings need two sets of seals → combined parasitic load ~ 500 KW

• Larger L/D → longer blades for same annular area → aero efficiency

• No need of separate compressor package → reduced cost.
Why Hybrid Gas Bearing for sCO2 Turbine?

1) Shorter Rotor → Reduced rotor flexibility → rotordynamically stable
2) For same L/D, longer blades → aero efficiency.
3) No parasitic losses from seals → 500 KW
4) Gas less viscous → Lower power loss in the bearing
5) Midspan bearing allows integral compressor → reduced cost.

HGB brings sCO2 rotor down into comfortable CSR regime

CSR = continuous speed
first UCS on rigid support (FCSR)
Why Dry Gas Seal in sCO2 Turbine?

- ~10% improvement in overall system efficiency (leakage + generator windage)

- Unlike steam Rankine cycles, leaked CO2 must be compressed as vapor back to main compressor inlet pressure of ~80 bar.

- Need multi-stage intercooled compressors → Large auxiliary compression load → efficiency penalty (figure on right)

- 0.6% total end seal leakage reduces net cycle efficiency from 50% to about 48.4%.

- High temperature DGS → eliminate need for thermal management schemes → reduce rotor span → better L/D → better Aero efficiency & rotordynamics.

- Aid 500 MW scale sCO2 turbine designs by allowing 24-36” diameter DGS design which does not exist today.
Project Objectives

- Develop coupled physics performance and life prediction framework for sCO2 turbomachines

- Thin film physics & fluid-structure interaction

- Corrosion of Ni alloys in sCO2

- sCO2 Phase Change and 2-Phase Heat Transfer

- Effect of sCO2 on LCF & Microstructure

- 3D Fracture Mechanics Models

- High Energy X-Ray Tomography
Hybrid Gas Bearing

- Combine hydrostatic and hydrodynamic load support
- Flexure pivot tilting pad bearing for stability
- Maintain very tight film thickness ~ mil
- Bearing is soft-mounted on s-Spring to provide compliance.
- Damping is achieved between the pad and supports via wire mesh to dissipate vibration energy
Hybrid Gas Bearing Performance Model

- Static Pressure: flow from supply pressure tube to bearing edge (guess recess pressure).
- Guess rotor position → determine film thickness → solve compressible Reynolds equation.
- Wire mesh damping and stiffness properties determined experimentally.
- Structural stiffness and damping matrices constructed from X,Y force equilibrium.

\[
\begin{align*}
\left[ \begin{array}{c}
F_{px} \\
F_{py}
\end{array} \right] &= \int_0^L \int_{\theta_1}^{\theta_2} \left( P^k - P_b \right) \left[ \begin{array}{c}
\cos \theta \\
\sin \theta
\end{array} \right] \cdot Rd\theta \cdot dy \\
F_b^k &= F_{D1}^k \left[ \begin{array}{c}
\sin \theta_p k \\
\cos \theta_p k
\end{array} \right] + F_{D2}^k \left[ \begin{array}{c}
\sin \theta_f k \\
\cos \theta_f k
\end{array} \right] + F_{S1}^k \left[ \begin{array}{c}
\sin \theta_{p1} k \\
\cos \theta_{p1} k
\end{array} \right] + F_{S2}^k \left[ \begin{array}{c}
\sin \theta_{p2} k \\
\cos \theta_{p2} k
\end{array} \right]
\end{align*}
\]

\[
\begin{align*}
\dot{m}_C^k &= C_D \cdot \frac{\left( \frac{D_c}{2} \right)^2 \cdot \pi \cdot P_s}{\sqrt{\gamma \cdot R \cdot T}} \cdot \sqrt{\frac{2 \cdot \gamma^2}{\gamma - 1} \cdot \left( \frac{P_{r}^k}{P_b^k} \right)^{2/\gamma} - \left( \frac{P_{r}^k}{P_b^k} \right)^{(\gamma+1)/\gamma}} \\
\dot{m}_{choked} &= \left( \frac{2}{\gamma + 1} \right)^{1/(\gamma - 1)} \cdot \sqrt{\frac{\gamma - 1}{\gamma + 1} \cdot \frac{D_c^2}{2 \gamma \cdot R \cdot T} \cdot \sqrt{\frac{2 \cdot \gamma^2}{\gamma - 1} \cdot \left( \frac{P_{r}^k}{P_b^k} \right)^{2/\gamma} - \left( \frac{P_{r}^k}{P_b^k} \right)^{(\gamma+1)/\gamma}}}
\end{align*}
\]

\[
\begin{align*}
h^k &= C + e_X \cos(\theta) + e_Y \sin(\theta) - r_p \cos(\theta - \frac{(\theta_1 - \theta_2)}{2}) \\
\frac{1}{R^2} \frac{\partial}{\partial \theta} \left( (h^k)^3 \frac{\partial P^k}{\partial \theta} \right) + \frac{\partial}{\partial y} \left( (h^k)^3 \frac{\partial P^k}{\partial y} \right) &= 6 \mu \frac{\partial}{\partial \theta} (h^k P^k)
\end{align*}
\]
Hybrid Gas Bearing Performance in sCO2 Turbine

Non-dimensional stiffness of HGB during sCO2 operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{xx}$</td>
<td>235</td>
</tr>
<tr>
<td>$K_{xy}$</td>
<td>-2.6</td>
</tr>
<tr>
<td>$K_{yx}$</td>
<td>-5.1</td>
</tr>
<tr>
<td>$K_{yy}$</td>
<td>312</td>
</tr>
</tbody>
</table>

Non-dimensional damping of HGB during sCO2 operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{xx}$</td>
<td>89</td>
</tr>
<tr>
<td>$C_{xy}$</td>
<td>21</td>
</tr>
<tr>
<td>$C_{yx}$</td>
<td>29</td>
</tr>
<tr>
<td>$C_{yy}$</td>
<td>48</td>
</tr>
</tbody>
</table>
Model Validation (in Air) using Pressurized Rotordynamics Tests on Hybrid Gas Bearing

- Static force
- Proximity probe
- Accelerometer

High speed motor

High resolution strain gages

Pressure feed lines

Hydraulic shaker

Pad rotations

Pad#3 and #4 Leading edge, average measurement and prediction

- pad #3 and #4 prediction - shifted to match initial relative point
- pad #3 and #4 average measurement

Strain in S-Springs

- Strain gage #1, measurement
- Prediction at gage #1 location
- Strain gage #2, measurement
- Prediction at gage #2 location

Strain gage #1

Strain gage #2, and #3

Large orbit single frequency excitations → Bearing response due to unbalance

Parameter Identification

$H_y(\omega) = K_y - \omega^2 M_y + i\omega C_y$

System's complex dynamic stiffness

Physical representation of rotor-bearing system's force coefficients:

Dynamic excitation
Frequency: 10-250 Hz

Acceleration
Displacement
Hybrid Gas Bearing Load Mission in sCO2 Turbine

Coupled Fluid-Structure-Thermal Interactions in sCO2

Thin Film Physics + Rotordynamics + System Level Fluid-Thermal-Structural

Validation Tests:

Turbine loading mission

Total Life

Loading Mission Cycle For Life Prediction
Dry Gas Seal Performance Models

- Assess Performance Risks
- Feed into Life Model
- Design Optimization for large MW sCO2 turbines

**Thin Film Physics:**

\[
\frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{p h^3}{\mu} \frac{\partial P}{\partial \theta} \right) + \frac{\partial}{\partial r} \left( \frac{r p h^3}{\mu} \frac{\partial P}{\partial r} \right) = 12 \omega r \frac{\partial}{\partial \theta} \left( h p \right)
\]

**Coupled Fluid-Structure Interaction:**

**Seal (system) level**

\[
x(t) = \begin{bmatrix} 0_{2N\times N} & K_{2N\times N} & x(t) + b(t) \end{bmatrix} \begin{bmatrix} \tilde{M}^{-1} & 0 \end{bmatrix} x = \begin{bmatrix} y_1 & y_N \end{bmatrix}
\]

**Segment Level**

\[
M = \begin{bmatrix} M_{11} & 0 & \cdots & 0 \\ 0 & M_{12} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & M_{NN} \end{bmatrix},
K = \begin{bmatrix} K_{11} & K_{12} & \cdots & K_{1N} \\ K_{21} & K_{22} & \cdots & K_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ K_{N1} & K_{N2} & \cdots & K_{NN} \end{bmatrix},
\]

\[
y = \begin{bmatrix} y_1 \\ y_N \end{bmatrix}
\]

**DOF Level**

\[
K_a = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} & k_{yx} & k_{yy} & k_{yz} \\ k_{xy} & k_{yy} & k_{yz} & k_{yx} & k_{yy} & k_{yz} \\ k_{xz} & k_{yz} & k_{zz} & k_{xz} & k_{yz} & k_{zz} \\ k_{yx} & k_{xy} & k_{xz} & k_{yx} & k_{xy} & k_{xz} \\ k_{yy} & k_{yx} & k_{yz} & k_{yy} & k_{yx} & k_{yz} \\ k_{yz} & k_{zy} & k_{zz} & k_{yz} & k_{zy} & k_{zz} \end{bmatrix},
K_i = \begin{bmatrix} k_{i,x} & k_{i,y} & k_{i,z} \\ k_{i,y} & k_{i,y} & k_{i,z} \\ k_{i,z} & k_{i,z} & k_{i,z} \end{bmatrix},
\]

\[
M_i = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & 0 & m \end{bmatrix},
\]

\[
y_i = \begin{bmatrix} \chi \\ \gamma \\ \psi \end{bmatrix}
\]

**Effect of Turbine Axial Transients**

\[
r = r_g e^{\theta \tan(\alpha)}
\]

**Hydrodynamic Pressure at Interface**

**Tilt & Coning**

**ND1 vibrations**
Hydrodynamic Force & Stiffness Variation with Spiral Angle

Normalized Hydrodynamic Force (dimensionless)

Pitch = 20 deg.

Hydrodynamic Stiffness (lbf/ml)

Force Generation Purely from Hydrodynamic Action (Hydrostatic Force Subtracted)

- α = 30 deg., DWR = 0.14
- α = 15 deg., DWR = 0.14
- α = 40 deg., DWR = 0.14
- α = 15 deg., DWR = 0.57
- α = 30 deg., DWR = 0.57

Hydrodynamic Stiffness (lbf/ml)

Force Generation Purely from Hydrodynamic Action (Hydrostatic Force Subtracted)
Pitch : 20 deg.

Film Stiffness (lbf/ml)

- α 15, DWR = 0.14
- α 15, DWR = 0.57
- α 30, DWR = 0.57

T goes up → Viscosity goes up → pressure goes up

Riding Gap (mil)

0.2 mil

0.4 mil

0.6 mil

Riding Gap (mil)
sCO2 Specific Perturbations

Risks addressed through Advanced Models
- Supercritical → Liquid → Dry Ice.
- Sonic Transition @ DGS interface
- Density → Local speed of sound → Mach #
- High Biot #, High Nusselt # → Large thermal stresses, coning

Density

Speed of Sound

Mach # Variation

Thermal-Structural Risks

Flow Reversal
sCO2 Phase Change & Surface Tension Studies

sCO2 Phase Diagram

Liquid-gas interface

Pressurization Path (1→2→3)

- Liquid
- Gas

De-Pressurization Path (3→4)

- Liquid
- Gas

3→4: Pressure reduced isothermally to cause CO2 transition from supercritical state (a) to a complete gas phase (d).

(a) : Supercritical State

(b, c) : Crossing phase boundary, appearance of meniscus & surface tension

(d) : Pure gas phase CO2 remains as pressure (65 bar) falls well below the critical pressure (73 bar).

Experimental Setup

Information on this chart is delivered with LIMITED RIGHTS in accordance with legend on the cover page.
Phase Change and 2-Phase Flow Model

Liquid phase described using incompressible Navier-Stokes equations:
\[
\rho_L \frac{\partial u_L}{\partial t} + \rho_L (u_L \cdot \nabla) u_L = \nabla \cdot \left[ -p_L \mathbf{I} + \eta_L (\nabla u_L + (\nabla u_L)^T) \right] + \rho_L \mathbf{g}
\]

Vapor phase described using Weak form of Navier Stokes Equation:
\[
\rho_v \frac{\partial u_v}{\partial t} + \rho_v (u_v \cdot \nabla) u_v = \nabla \cdot \left[ -p_v \mathbf{I} + \eta_v (\nabla u_v + (\nabla u_v)^T) - \left( \frac{2}{3} \eta - \kappa_{dv} \right) (\nabla \cdot u) \mathbf{I} \right] + \rho_v \mathbf{g}
\]
\[
\frac{\partial \rho_v}{\partial t} + \nabla \cdot (\rho_v u_v) = 0
\]

Conduction Equation for the vapor phase:
\[
\rho_v C_p \frac{\partial T_v}{\partial t} + \rho_v C_p (u_v \cdot \nabla) T_v = -\nabla \cdot \kappa_v \nabla T_v
\]

Boundary conditions at liquid-vapor phase boundary:
• 3 forces act on the liquid @ interface → natural boundary condition for liquid can be written as:
\[
n \cdot \left[ -p_L \mathbf{I} + \eta_L (\nabla u_L + (\nabla u_L)^T) \right] = \dot{m} (u_L - u_v) + \sigma \kappa n + n \cdot \left[ -p_v \mathbf{I} + \eta_v (\nabla u_v + (\nabla u_v)^T) \right]
\]

reaction force due to the acceleration of the vapor away from the liquid surface
Surface Tension
Sum of pressure & viscous forces acting on the liquid from vapor

• State-of-the-Art Code developed in House.
• Study phase change risks in sCO2 compressors.
• Nucleation vs Residence time scales.
• Design effective sCO2 heat exchangers.
• Condensation and erosion predictions.
Phase Change and 2-PhaseFlow Model using Level Set Method

Water Boiling

CO2 Boiling

- Large local metal surface temp. rise.
- Uncertainty in HTCs
- Performance risks.
- Oxidation acceleration
- Life debit.

Transition to film boiling
Phase Change and 2-PhaseFlow Model using Level Set Method
Dry Gas Seal Model Validation Tests in 10 MWe Sunshot sCO2 Expander

- **Inlet Side**
  - Seal Gas Supply
  - Seal Vent
  - To Process; Seal Gas LP Reference
  - To Bearing Vent

- **Exit Side**
  - Seal Gas Supply
  - Seal Vent
  - To Bearing Vent

**Stream**

<table>
<thead>
<tr>
<th>Stream</th>
<th>T (°C)</th>
<th>P (bara)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seal Supply (CO₂)</td>
<td>100</td>
<td>89.6</td>
</tr>
<tr>
<td>Separation Air</td>
<td>26</td>
<td>1.19</td>
</tr>
<tr>
<td>Seal Vent</td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>

Low Cycle Fatigue Tests on Ni Alloys in sCO2
Low Cycle Fatigue Tests on Ni Alloys in sCO2

Inconel 617
- High corrosion resistance
  - Coarse grain
  - Single phase alloy
  - Cr rich
- Intergranular particles (delta)
- Transgranular particles (carbides)

Inconel 718
- Good LCF properties
  - Fine grain
  - Dual phase alloy
  - Precipitates at grain boundaries

Thumbnail pattern of Natural crack initiation on sCO2 side

SEM of crack Initiation site

Find This
- Dislocation motion in most favorably orientated grains.
- Formation of extrusion and intrusion types of defects by dislocation accumulation.

Tested in Air
- Failure initiated on the OD

Tested in sCO2
- Failure initiated on the ID
Differences in Air vs sCO2 Crack Initiation Mechanisms

Air

Air

sCO2

sCO2

sCO2

CSP Program Summit 2016
• No significant LCF life debit is observed in IN718 by sCO₂ at 550°C, 0.7% max strain, 20 cpm.

• Little lower life observed for 0.5 % strains due to longer exposure times resulting from larger number of cycles to failure.

• It is expected that with longer hold-times, sCO₂ environment may be more aggressive – resulting in lower fatigue life.
Corrosion of Ni base Super Alloys in sCO2
Corrosion of Ni base Super Alloys in sCO2

Find Species Diffusion using Spectroscopy

3 Types of sCO2 Corrosion Attacks
- pitting
- Internal attack
- Voids

Effect on Surface Properties

Evolution of Corrosion with Time & Temperature

Chemical Kinetics Model

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Activation energy, Ea (Joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN617</td>
<td>$1.7 \times 10^6$</td>
</tr>
<tr>
<td>IN718</td>
<td>$9.3 \times 10^5$</td>
</tr>
</tbody>
</table>

Models for Crack Initiation, Crack Propagation & High Energy X-Ray Tomography
Models for Crack Initiation, Crack Propagation & High Energy X-Ray Tomography

Chemistry & Thermodynamics coupled Crack Initiation Model:

\[ N_i = A(\Delta \varepsilon_p)^{-m} \exp \left( \frac{q}{RT} \right) \left( \frac{1}{u} + t_n \right)^{-n} \]

Crack Initiation Model

6 GeV Synchrotron

X-Ray Tomography

After 15000 cycles: No micro cracks

After 30000 cycles: 3D crack evolution captured Non-destructively

Crack Propagation Model

Predicts Crack Evolution in 3D and # of cycles to final failure

Predicted Crack Propagation Rate
Using Bayesian Probabilistics Framework to Tie it All Together

**BHM Metamodel**

\[ y(x) \pm \epsilon(x) = \eta(x, \theta) + \delta(x) \]

1. Tuned parameters

2. Discrepancy model

3. Global sensitivity

4. Probabilistic Predictions

5. Predictive Model

**Simulation results**

\[ \eta(x, \theta) \]

**Prior Knowledge**

\[ \theta_j \]

**Experimental data**

\[ y(x) \pm \epsilon(x) \]

**Main Effects**

- Trend with confidence

**Uncertainty Prediction**

**Statistically Relevant Life Prediction**

**Initiation Life**

(Arrhenius model)

+ Propagation Life

(3DFAS)

= Total Life

**Principal Component Extraction**

- Gas_viscosity
- F_static
- Rotor_rpm
- Pressure
- F_static_x_Gas_viscosity
- Pressure_x_Gas_viscosity
- Rotor_rpm_x_Gas_viscosity
- F_dyn_freq
- F_static_x_F_dyn_freq
- F_static_x_Pressure
- Rotor_rpm_x_Pressure
- Rotor_rpm_x_F_static
- F_dyn_freq_x_Pressure
- Rotor_rpm_x_F_dyn_freq

**Uncertainty Prediction**

**Model Predictions:**

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>55,590</td>
<td>37,129</td>
</tr>
<tr>
<td>Np</td>
<td>5033</td>
<td>493.3</td>
</tr>
<tr>
<td>Ntotal</td>
<td>60,622</td>
<td>37,132</td>
</tr>
</tbody>
</table>

Information on this chart is delivered with LIMITED RIGHTS in accordance with legend on the cover page.
Milestones

**Phase 1 (completed):**
- Performance models for DGS & HGB
- Sonic Transition Models
- sCO2 Phase Change Models & Tests

**Phase 2 (completed):**
- sCO2 LCF and Corrosion Experiments
- sCO2 Chemical Kinetics & Oxidation
- 3D Crack Propagation Models
- High Energy X-ray Tomography.

**Phase 3 (in progress):**
- Crack propagation tests in sCO2
- Integrated Life Prediction Model
- Bayesian Probabilistics Performance and Life Framework
Path to Market

- Mature 10 MWe sCO2 turbine technology for CSP by 2020.
- DOE STEP Program: 50 MW Power Plant Demo
- 500 MW sCO2 turbine ~ 2025-2030
- Other Applications: Waste Heat Recovery, Transportation
Conclusions

• Multi-scale coupled physics models to predict dynamic performance of HGB and DGS are developed.

• The models try to capture sCO2 specific phenomena like sonic transitions, possibility of phase change, flow induced and rotordynamic instabilities and large perturbations in apparent heat transfer coefficients.

• The output of performance model is fed into 3D fracture mechanics based life prediction framework.

• Test campaigns to characterize corrosion of Nickel base super alloys in sCO2 environment are conducted and chemical kinetics models are built.

• LCF behavior of Ni base super alloys in high pressure, high temperature sCO2 is also being investigated using a novel experimental setup.

• Bayesian hybrid probabilistic models are developed to quantify uncertainty in multi-physics models and to validate models with statistical confidence.

• This coupled physics framework is a valuable tool to design a wide variety of sCO2 turbomachines and heat exchangers, analyze their performance in supercritical and trans-critical mission cycles and predict their life for long term durability of sCO2 turbomachines.