Development of sCO₂ Turbomachinery and its Application to Energy Storage

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Thermal-Mechanical-Chemical-Energy-Storage Workshop
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Introduction

- Energy storage technologies are rapidly developing in response to increasingly large fluctuations in power demand and availability from intermittent resources including renewables

- New cycles require custom turbomachinery designs

- \( \text{SCO}_2 \) power cycles are being developed for both indirect and direct fired configurations

- \( \text{SCO}_2 \) cycles being considered for energy storage

- This presentation focuses on development of \( \text{SCO}_2 \) turbomachinery to meet these challenging requirements
Thermochemical ES: CO₂ Phase Change

- Combined with Thermal ES, which uses excess solar energy and stores in molten salt.
- Excess energy from the grid is used to cool liquid CO₂ to solid (dry ice)
- Release heat from salt to expand CO₂ from solid to supercritical fluid
- Turbomachinery Integration
  - Turbine development for high-temperature, high-pressure CO₂
- Current TRL: 2-3
  - Component tests
- Technology Gaps
- Expected Performance
  - 68% efficiency
- R&D Activities
  - GE GRC through the ARPA-E FOCUS program
  - Echogen Power Systems with ARPA-E DAYS
Trans-critical CO2 cycle

- Permits water ice cold storage, modest hot storage temperature (580°C)
- Competitive with ideal gas cycles at higher pressures

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ideal gas cycle</th>
<th>Transcritical CO2 Alt 1</th>
<th>Transcritical CO2 Alt 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round Trip Efficiency</td>
<td>%</td>
<td>57.86</td>
<td>51.54</td>
</tr>
<tr>
<td>Heat Pump COP</td>
<td></td>
<td>1.31</td>
<td>1.78</td>
</tr>
<tr>
<td>Engine Efficiency</td>
<td></td>
<td>0.44</td>
<td>0.29</td>
</tr>
<tr>
<td>Charging Pr</td>
<td></td>
<td>3.82</td>
<td>7.63</td>
</tr>
<tr>
<td>Discharging Pr</td>
<td></td>
<td>5.17</td>
<td>6.78</td>
</tr>
<tr>
<td>Cycle Max Temperature</td>
<td>°F</td>
<td>1050.0</td>
<td>610.0</td>
</tr>
<tr>
<td>Cycle Min Temperature</td>
<td>°F</td>
<td>-73.6</td>
<td>23.0</td>
</tr>
<tr>
<td>Cycle Max Pressure</td>
<td>psia</td>
<td>500.0</td>
<td>3905.0</td>
</tr>
</tbody>
</table>


Contribution by Jason Kerth, Siemens Energy

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Echogen Hybrid PTES

• PTES runs as a heat pump using heat of compression
  • Molten salt thermal storage
• Condensing SC\textsubscript{O}2 Charge Cycle for cold storage
  • Research proposed to understand effects of multi-phase flow on turbine reliability
  • Will utilize SC\textsubscript{O}2 pump loop at SwRI to test condensing turbine
• SwRI and Flowserve supporting development

GE SCO2/Steam Pumped Heat Cycle

- SCO2 heat pump with molten salt thermal storage for charge cycle up to 480°C (current SCO2 compressor limit)
- Electric resistive heating used to heat to 565°C
- Discharge cycle using standard water steam cycle.
- Cold storage as water
- Leverages existing equipment as much as possible

MAN/ABB Electro-Thermal Energy Storage (ETES)

- Provides electricity, heating, and cooling on demand for variety of industries and buildings
- Targeting process industries, data centers, power producers, utilities, and large facilities
- Leverages HOFIM™ hermetically sealed compressor
- Use ice for cold storage and hot water for hot stores
- Using hot and cold stores directly results in overall process efficiency up to 70%.

EnergyDome Liquid CO2 Storage

- Compresses CO2 from atmospheric pressure to pressure that can be liquified at ambient temperature (700-1000 psi, 48-69 bar)
- Heat of compressor stored as hot water
- Discharge cycle expands through reheat turbine
- Low pressure CO2 storage in large dome.
- Claim RTE>75%
- Not site dependent

https://energydome.it/co2-battery/
**Technology Summary**

- Apply liquid oxygen (LOX) storage to a natural gas, direct-fired $\text{SCO}_2$ power cycle
- Air Separation Unit (ASU) operated during low LMP and at part-load during medium LMP
- LOX stored and utilized during high LMP

**Technology Impact**

Provides up to 20% greater power plant output (with the same fuel burn) during high demand by reducing the parasitic load of the ASU while maintaining zero NOx and SOx emissions and producing pipeline quality CO$_2$.

**Proposed Targets**

<table>
<thead>
<tr>
<th>Metric</th>
<th>State of the Art</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Cost (Fuel) $/\text{MWh}-\text{net}$</td>
<td>NGCC with CCS</td>
<td>Allam Cycle with O2 Storage</td>
</tr>
<tr>
<td>$45.87$</td>
<td>$34.76$</td>
<td></td>
</tr>
<tr>
<td>Net Plant Efficiency</td>
<td>50.6%</td>
<td>66.8% (ASU burden removed)</td>
</tr>
</tbody>
</table>

Carbon-free natural gas fired power generation with 20% less operating cost using liquid oxygen energy storage.
Introduction to sCO2
A fluid is supercritical if the pressure and temperature are greater than the critical values:

- Critical pressure: $P_{\text{crit}} = 7.37 \text{ MPa (1070 psi)}$
- Critical temperature: $T_{\text{crit}} = 31^\circ \text{C (88^\circ F)}$

The diagram shows the supercritical region for CO₂ with $P_{\text{crit}} = 7.37 \text{ MPa}$ and $T_{\text{crit}} = 31^\circ \text{C}$. The two-phase region is indicated as well. The diagram is based on REFPROP (2007) and EOS CO₂: Span & Wagner (1996).
Fluid density sharply decreases near the critical point

REFPROP (2007)
Cycle Efficiency

Recompression Brayton Cycle
Motivation for sCO2 Cycles over Steam

20 MW Steam Turbine

15 MW sCO2 Turbine

180 lb rotor
7” rotor tip diameter
27,000 rpm
20,000 hp!

Vapor properties at 25°C (77°F) condenser
Sunshot Program (2013-2018)

- Develop and test 1 MW scale turbine and recuperator
- Partners: SwRI, General Electric GRC, Thar Energy, Aramco Services Co., Navy Nuclear Laboratory, and Electric Power Research Institute (EPRI)
- Developed 10 MWe Turbine Frame Size with 1 MW flow path
- Funded by EERE within US Dept. of Energy
- Completed Testing in Dec. 2018 Achieving Full Temperature (715°C), Full Pressure (250 bar), and Full Speed (27,000 rpm)
- At the time, the Highest Temperature SCO2 Turbine in the Literature
- New cycle required development of new expander, compressor, and recuperator
SUNSHOT: Simple sCO\textsubscript{2} Recuperated Cycle for Test Loop
Sunshot Turbine Design

10 MW Gen

INLET

HOLES PATTERN BALANCE PISTON DAMPER SEAL

ISFD BRG

NOZZLES WITH SWIRL BRAKES

EXIT

ISFD BRG

SHAFT DIA. 3in (76mm)

SHAFT DIA. 3in (76mm)

36in (914mm)
Rotor Design

4-Stage Axial Flow Design
Thermal Management Region

• Temperature gradient at shaft ends required due to dry gas seals

Temperature profile in the shaft and stator piece in the thermal management region

(Blue = 50°C, Red = 715°C) (Kalra, et. al, 2014)
Rotordynamics

- Long flexible rotor and high gas density makes rotordynamics challenging

Rotordynamic Prediction for First Critical Speed

Rotordynamic Experience Chart from Moore (2006) with Sunshot Turbine Rotor Added
Sunshot Test Loop Components

- Dry Gas Seal Panel
- Recuperator
- IN625 Piping
- IN740H Piping
- Heater
- Lube Oil Drain
- Lube Oil Supply

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Assembled Turbine Casing on Operating Stand
# Turbine Design Operating Points

<table>
<thead>
<tr>
<th></th>
<th>Speed (rpm)</th>
<th>Turbine Inlet Temp. °C (°F)</th>
<th>Turbine Inlet Pressure bar (psi)</th>
<th>Turbine Exit Pressure bar (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Design Point</td>
<td>21,000</td>
<td>550°C (1022°F)</td>
<td>~200 bar (3000 psi)</td>
<td>80 bar (1160 psi)</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; Design Point</td>
<td>27,000</td>
<td>715°C (1319°F)</td>
<td>~250 bar (3625 psi)</td>
<td>80 bar (1160 psi)</td>
</tr>
</tbody>
</table>
Heater at 1750F (954C)
Loop Temperatures

6 Hour 715C Endurance Test
Sunshot Measured Thermal Seal Performance

Temperature vs Axial Location

Temperature vs Inlet Journal Bearing [in]

- Blue line: Sunshot Seal
- Orange line: FOCUS Seal
Sunshot Turbine Summary

• Turbine performance met mechanical and performance objectives.
  • Achieved design temperature of 715°C, design speed of 27000 rpm, and near design pressure of 250 bar.
  • Highest temperature SCO₂ turbine in the literature.
  • Thermal seal maintained acceptable dry gas seal operating temperature with near linear profile.
  • Vibration well less than 0.5 mils with no signs of instability
  • Low critical speed response (good bearing damping and balance)
  • Good thrust balance and low thrust bearing temperature
  • Low radial bearing temperatures following clearance modification
  • Many shutdown transients tolerated
    • Some leakage experienced out case joints due to loss of bolt preload
    • Being addressed with single piece case design with STEP
  • Modified dry gas seal panel maintained warm seal gas preventing dry ice formation
Testing has leveraged existing SwRI Sunshot loop with modifications.
Apollo Compressor Design Goals & Challenges

• Main compressor has very high pressure rise (2400 psi) and low head due to high inlet density
  • Requires high power, small diameter impeller
• Compressor casing that would be rated to 4,800 psia (25% above peak operating pressure)
  • Thick walls and large heads
  • Large retaining features (bolts or shear rings)
• Compressor package that included both Main and Bypass compressor that could be directly coupled to turbine for the sCO$_2$
power cycle
  • Longer rotor with large mass in middle of the shaft
  • High critical speed ratio of operation with high density flow
• Handle density swings up to 2X and flow ranges up to 3X
  • Meet target discharge pressure and mass flow over a wide range of suction pressures and temperatures
  • Requires flow control enhancement using Actuated IGVs
• Rotating speed of 27,000 rpm to match target turbine
  • High speed seals (same as Sunshot)
• Internal Bundle design
  • Ease of assembly / disassembly
  • Requires a tightly packaged system with many critical internal features
Design Evolution

- Advance the design from conceptual sketch to manufactured hardware
- Pass various design review (Conceptual, Preliminary, and Detailed)
- Meet design codes
  - API 617: Compressor Packages
  - API 684: Rotordynamic
  - ASME VIII-2: Pressure containment
  - PTC 10: Compressor testing
- Full drawing and manufacturing review of all components
Variable IGV Design

17 Radial IGVs in baseline design

IGV Mechanism using external actuator
Assembled Compressor Rotor

- Built-up Rotor Design with Tie-bolt
- Impeller Hub Manufactured Integral to Impeller due small impeller hub diameter
- Rotordynamic stability a concern due to high fluid density
- Bearing modifications required to manage fluid induced forces due to high density by eliminating squeeze film dampers
- Performance data shows strong effect of inlet temperature

Test Data

Choke line shift due to inlet speed of sound

+10° IGV

-30° IGV
Apollo Compressor Testing

Notable Achievements:

- **World Record density:** 720 kg/m$^3$
- Smallest impeller manufactured by BHGE.
- Mechanically well-behaved demonstrating high pressure CO$_2$ compression possible.
- Highlighted challenges with measuring CO2 properties near the liquid-vapor dome.
Ultra High Efficiency Integrally-Geared sCO2 Compander
(SwRI, Hanwha for DOE EERE) (2017-2021)

• Design a sCO2 integrally geared compander (IGC)
  • Combining compression and expansion stages into a single integrally geared housing connected to a low speed motor/generator.

• Benefits:
  • Reduced footprint
  • Potential cost reduction up to 35%
  • Utilizes a low speed commercially available driver/generator
  • Modular (Small Industrial [5MW] to Small Utility [50 MW])
  • High efficiency over a wide range of operating conditions
  • Improved cycle controllability
  • Reduced mechanical complexity ➔ improved reliability and reduced maintenance

• Achieved 720°C and full pressure with low vibrations
Supercritical Transformational Electric Power (STEP) Pilot Plant Test Facility (2017-2022)

- Design, construct, and operate a 10 MWe sCO2 Pilot Plant Test Facility
- Advance the state of the art for high temperature sCO2 systems
- Project team includes Gas Technology Institute, SwRI, and General Electric Global Research
- Six year, $110 million project with $80 million funded by DOE-NETL
- Test facility located at SwRI
**STEP 10 MWe Turbine**

Monolithic Rotor and Stators

Inlet Plenum

Exit Plenum

Exit Turn and Thermal Seal

Thermal Seal

Air Vent

Generator Coupling

Tilt Pad Bearing

Oil Drain

Dry Gas Seal

Balance Piston

Inlet Nozzle

Stage 3 Stator

Stage 2 Stator

1-Piece Fabricated Inconel Casing

Sunshot Turbine

- Sunshot was Design Basis
- Monolithic Fabricated Case
- Same One-Piece Rotor
- Similar bearing and dry gas seal design
- 3 vs. 4 stages
STEP 10 MWe Turbine Skid

- Bypass Compressor
- Dry Gas Seal Panel
- Bypass Compressor Sub-skid
- Gearbox
- Bypass Compressor Sub-skid
- Generator
- Turbine Stand
- Turbine
- Gearbox
Direct-Fired Oxy-Fuel Turbine Development

- Developing a 300 MWe Utility Scale Oxy-Fuel Turbine with 1150 °C turbine inlet temperature at 300 bar using Allam-Fetvedt cycle
- Significantly improve the state-of-the-art for thermal efficiency (approaching 60%) and results in a high-pressure stream of CO₂ simplifying carbon capture, making the power plant emission-free.
- Funded under the DOE 21st Century CT program further developing oxy-fuel turbine design and performing material, combustion kinetics, and heat transfer testing for both natural gas and coal syn-gas.
Summary

• Unique power or energy storage cycles require unique equipment designs to implement them
• SCO2 power cycles showing good promise to improve cycle efficiencies
• High fluid density and low cycle pressure ratio greatly reduces equipment size for SCO2 cycles
• SCO2 cycles have application to energy storage for both thermochemical and pumped heat applications
• For the direct-fired Allam-Fetvedt cycle, both fuel (hydrogen) and oxidizer (LOX) may be used to store energy
Questions?

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