Supercritical Carbon Dioxide Power Cycle Development Overview
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Ken Kimball has been actively involved with supercritical CO2 Brayton power cycle development since 2005 working at the Knolls Atomic Power Laboratory in Schenectady, NY, USA. This effort has included working closely with numerous University, National Laboratory and Industry groups. He has a BS degree in mechanical engineering from Worcester Polytechnic Institute and an MS degree in mechanical engineering from Rensselaer Polytechnic Institute. He has previously presented development progress at the Supercritical CO2 Brayton power cycle development symposiums in 2009 and 2011 and the ASME Turbo Conferences in 2012 and 2013.
Abstract

Bechtel Marine Propulsion Corporation (BMPC) is testing a supercritical carbon dioxide (S-CO₂) Brayton system at the Bettis Atomic Power Laboratory. The 100 kWe Integrated System Test (IST) is a two shaft recuperated closed Brayton cycle with a variable speed turbine driven compressor and a constant speed turbine driven generator using S-CO₂ as the working fluid. The IST was designed to demonstrate operational, control and performance characteristics of an S-CO₂ Brayton power cycle over a wide range of conditions. The IST design includes a comprehensive instrumentation and control system to facilitate precise control of loop operations and to allow detailed evaluation of component and system performance. A detailed dynamic performance model is being used to predict IST performance, support test procedure development and to evaluate test results. An overview of IST testing progress and plans is provided. Testing in the IST was initiated in 2012. Test operations to date included successful system startup, initial transition to electrical power generation, increased power operations and transition to load control testing using independent speed control of the turbo-machinery. Results of testing completed to date and future testing plans will be summarized.
Supercritical Carbon Dioxide Power Cycle Development Overview

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BMPC Development Program Overview:

- S-CO$_2$ Brayton Cycle Integrated Systems Test (IST)
  - Turbo-machinery (turbine, compressor, bearings, seals)
  - Control system (startup, power control)
  - Heat exchangers (shell and tube)
  - Practical considerations (mass control, instrumentation, system leakage)

- Compact Heat Exchanger Development
  - High pressure, compact, fatigue resistant, affordable

- MW scale development vision
  - Based on kW development
  - Scale-up issues
  - Transition from experimental to demonstration stage
S-CO$_2$ Integrated System Testing
IST Turbomachinery

Turbo-Generator

Thrust Bearing

Turbo-Compressor

Compressor/Diffuser

Turbine
Compressor Map

Model Prediction for Design Operating Conditions

Test Data
Power Increase Transient

- Initial Conditions: Hot Idle (540°F/37,500 rpm)
- TG speed increased
- TC speed increased in steps
- Compressor recirculation valve decreased in steps
- Water flow automatically controlled to maintain compressor inlet T

**Turbine-Generator Speed**

**Turbine-Compressor Speed**

**Recirculation Valve Position**
Power Increase Transient: Heat Exchanger Heat Duties

Intermediate Hx

Recuperator

Precooler

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Intermediate Hx

Recuperator

Precooler

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Heat Duty (kW)

Time (seconds)

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Heat Duty (kW)

Time (seconds)

---

Heat Duty (kW)

Time (seconds)
IHX Heat Transfer

![Graph showing measured vs. predicted heat transfer for different methods: HTRI w/REFPROP, HTRI w/VMGThermo, Dittus-Boelter. The graph includes a dashed line indicating measured = predicted.](image-url)
Precooler Heat Transfer

![Graph showing measured vs. predicted heat transfer for different shells. The graph compares the heat transfer measured in kilowatts (kW) against the predicted heat transfer. The data points are represented by green circles for shells in series, blue triangles for Shell 1, and red diamonds for Shell 2. The dashed line indicates where measured equals predicted heat transfer.]
Operational Experience
- 100 kWe Integrated System Test
- Shakedown started Fall 2011
- Over 165 hours of Brayton system operation
- Achieved 40% of design power

Design Considerations
- Off-design/transient model valuable for startup & low power operation
- Good experience with Grayloc & Swagelok fittings and ANSI flanges
- Thermal stresses need considered early for compact arrangement

Loop Cleanliness
- S-CO\textsubscript{2} is a great solvent
- Material quality and cleanliness controls are important
- EPDM acceptable, Viton and Teflon tape problematic
- Turbine nozzle erosion believed to be caused by debris in system

System Fill and Leakage
- IST uses Coleman Instrument grade (99.99%) CO\textsubscript{2} for fill
- Three cycles of pulling vacuum and filling to atmospheric pressure before full fill
- Low leakage levels from valve stem packing and large shaft seals

Instrumentation
- Marlin Type T SLE thermocouples
- Rosemount pressure transducers
- MicroMotion Elite Coriolis meters
- REFPROP calculated density (T&P) agrees well with measured density
This loop design shows how recompression control features could be placed in the IST, allowing loop hydraulic control for startup, heatup and low power operation.
IST Up-Power Maneuver in Recompression Configuration

Using end states that have been optimized for adequate surge margin this up-power transient shows good performance, with minimal under/over shoot.

Up-power rates >1%/s would be possible for a well designed recompression loop.
S-CO$_2$ Heat Exchanger Development
Heat Exchanger Testing

Testing Conditions:
Heat Input/Rejection 20-90 kW
Pressure: ≈1,200-1,500 psi
Temperature: ≈300-500°F
Flow rate: ≈2-3 lbm/second
Recuperator Designs Tested

**WavyFin**

$\beta = 3,300 - 4,500 \text{ m}^2/\text{m}^3$

**Wire Mesh**

$\beta = 7,000 - 8,000 \text{ m}^2/\text{m}^3$
Folded Wavy-Fin Results

Prototype demonstrated thermal-hydraulic performance.
Summary of Progress to Date
S-CO$_2$ Integrated System Testing

- IST demonstrating controllability of a two shaft simple S-CO2 Brayton cycle
- Normal power operation over range of power levels up to ~50 kWe has commenced
- TRACE transient modeling:
  - Validation has commenced
  - Approaching real time execution
  - Demonstrates controllability of re-compression cycle
S-CO$_2$ Heat Exchanger Development

- IST heat exchangers meeting expectations and validating performance models
- More compact/fatigue resistant heat exchangers being designed, fabricated and tested in dedicated 300kW test facility
MW Scale Development
Supercritical CO$_2$ Power Cycle Development Approach

**Fundamental Testing**
- Fluid Behavior
- Safety Implications
- Material Behavior

**Concept Development**
- Sandia Closed Brayton Loops

**Small Scale System and Component Tests**
- Small System Test
- HX Development & Test

**Large Component Development**
- Operational Test
- Integrated System Test
- Turbomachinery Performance
- Heat Exchanger Performance
- Validated Design Tools

**Large Scale System Test**
- Power Plant Concept Development

**Component and System Modeling Development**
Path to S-CO$_2$ Power Cycle Commercial Implementation

Component Development

- BMPC
- kW scale
- SNL
- SunShot
- MW scale
- Echogen
- GE

STEP Pilot Plant
~10 MWe FY16

Pre-Commercial Demo
~30-50 MWe FY20

Applications:
- Oxy-Fuel / Clean Coal
- Concentrated Solar Power
- High Temperature Nuclear
- Geothermal energy
- Navy Nuclear Propulsion
FY??

Materials Development

Engineering Design - Analysis Codes - Component Specifications
Bearings & Seals
Turbomachinery - Thermal Coatings - Internal cooling
Controls
Heat Exchangers
Chemistry Control
Test loop component development - heater

Technology Development

Current

Time

Supercritical CO$_2$ Power Cycles Symposium September 9-10, 2014