S-CO$_2$ Brayton Loop

Transient Modeling

The 4$^{th}$ International Symposium on Supercritical CO$_2$ Power Cycles

September 9 & 10, 2014
Outline

- Background

- Model Results and Comparisons with Test Data
  - Steady State Heat Balance
  - Transient
    - Turbomachinery Start-up
    - Power Transients

- Next Steps/Model Updates
  - NIST REFPROP/FIT
  - Test data

- Summary
Background

- Integrated Systems Test (IST)
  - Characteristics
    - Recuperated Closed Cycle Brayton
    - Rated power 100kWe
    - Power and Compressor Turbines in Parallel
    - Constant Speed Turbine Generator
    - Generated power $\propto$ Compressor Speed
    - Fixed inventory
  - Purpose
    - Operational experience
    - Demonstrate system control
    - Validate transient model
Background: Integrated Systems Test
Background: Integrated Systems Test
Background: IST Transient Model

IST Transient Model
• Built using TRACE and SNAP GUI
• Heat Source to Heat Sink
• Developed compressible fluid modeling methods
• Developed control systems

Hot Oil System

S-CO₂ Brayton Loop

S-CO₂ Brayton Loop Control

Chilled Water System
Steady State Comparison: Updated Model

Test

Oil to CO2 (OHX1)
495 kW
540.9 F
54,775 rpm

Power Turbine
PR: 1.40
1702 psi

C-Drive Turbine
PR: 1.40
1695 psi

538.8 F
2043 psi

Recuperator
1203 kW
1144 F
2059 psi

51%

Model

Oil to CO2
488.6 kW
540.9 F

Generator
36.5 kW
15861 W

Power Turbine
PR: 1.37
eff: 0.801
52.4 kW

C-Drive Turbine
PR: 1.37
eff: 0.796
46.2 kW

Recuperator
1197.9 kW
114.5 F
2034.7 psi

 transient time
6000.2
## Steady State Comparison: Updated Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test</th>
<th>Pretest TRACE Model</th>
<th>TRACE Model With adjusted compressor map</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor PR</td>
<td>1.45</td>
<td>1.37</td>
<td>1.43</td>
</tr>
<tr>
<td>Compressor Exit Temperature (F) [K]</td>
<td>113.5 [318.3]</td>
<td>113.2 [318.1]</td>
<td>114.5 [318.8]</td>
</tr>
</tbody>
</table>
IST Startup

Phenomenon considered during turbomachinery startup

- Compressor surge
- Reverse Turbine Flow
- Gas Foil Bearing Lift-off

Target Conditions for IST Turbomachinery Startup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine inlet temperatures</td>
<td>165°F (Z = 0.7)</td>
</tr>
<tr>
<td>Compressor inlet temperature</td>
<td>100°F</td>
</tr>
<tr>
<td>Compressor inlet pressure</td>
<td>1230 psia</td>
</tr>
<tr>
<td>Turbine bypass valve</td>
<td>Shut</td>
</tr>
<tr>
<td>Compressor recirculation valve</td>
<td>83% open</td>
</tr>
</tbody>
</table>
IST Startup: Comparison between Model (left) and Test data (right) for Compressor Startup – Shaft Speed and Main Loop Flows

Model

Test
IST Startup: Comparison between Model and Test for Turbine Compressor Startup – Shaft Motor Generator Powers and CO₂ Pressures

**Graphs:**
- **Motor Generator Power (kW):**
  - Model: Smooth curve.
  - Test: Peak and drop.
- **Compressor CO₂ Pressure (psia):**
  - Model: Steady increase.
  - Test: Gradual increase.
- **Power (kW):**
  - CMG1 Compressor Power: Steady increase.
- **Pressure (psia):**
  - CP1: Pressure at compressor inlet.
  - CP2: Pressure at compressor outlet.
IST Startup: Comparison between Model and Test for Turbine Generator Startup – Shaft Speed and Main Loop Flows

**Model**

- Brayton Shaft Speed (rpm)
- Time (seconds)
- Compressor Shaft
- Turbine Generator Shaft

**Test**

- Speed (RPM)
- Time (seconds)
- CBN19: CMG1 Compressor Speed
- CBN11: CMG2 TG Speed

- Brayton Loop CO2 Flows (lbm/s)
- Time (seconds)
- Compressor
- Comp Turbine
- Power Turbine
- Comp Recirculation

- Flow (lbm/s)
- Time (seconds)
- CF1: flow at Compressor inlet
- CF2: flow at Comp Turbine outlet
- CF3: flow at Power Turbine outlet
- CF4: flow at Compressor Recirculation
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

**Graphs:**
- Turbine-Generator Speed
- Turbine-Compressor Speed
- Recirculation Valve Position
Power Increase Transient: Turbine Generator Power

- TEST DATA: TC shaft speed
- MODEL: TC shaft speed

- TEST: TG Power
- MODEL: TG Power
Power Increase Transient: Cooling Water Control Valve Position, Flow Rate and Compressor Inlet Temperature
Power Increase Transient: Heat Exchanger Heat Duties

Intermediate Hx

Recuperator

Precooler

[Diagrams of heat exchanger systems with data plots showing heat duty over time for IHX, Recuperator, and Precooler]
Power Increase Transient: Comparison of Compressor Operation
Factors that Influence Runtime

- **CPU time** *(clock time)* is a function of
  - Computer Hardware (RAM speed, etc.)
  - Model Complexity
    - Component nodalization
    - Fluid property models and interrogation (PG-1®, Water, CO₂, etc.)
  - Transient Rate of Change
    - Heat up/Power Transients/Turbomachinery startup/etc.
  - *Model/Physical time*: time of actual transient (hour heat up)

- Up until now: *Model Time* $<<$ *CPU time*
  - Root cause - largest contributor was fluid property calls

- Now: *Model Time* $\approx$ *CPU time*
  - Change is the replacement of NIST property calculations with commercial package (FIT) [Northland Numerics]
NIST/FIT Comparison: Benchmarking

- Suite of 15 transient runs
  - Range in duration from 50 to 4000 seconds (physical time)
  - Include entire range of operations
    - Cold (150°F) with both shafts off
    - Start up
    - Configuration of CWS
    - Heat up/Power Transients

<table>
<thead>
<tr>
<th>Run Name</th>
<th>Run Id</th>
<th>Model Run Description</th>
<th>NIST model time (seconds)</th>
<th>NIST CPU time (seconds)</th>
<th>NIST to Real Time</th>
<th>FIT model time (seconds)</th>
<th>FIT CPU time (seconds)</th>
<th>FIT to Real Time</th>
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<tbody>
<tr>
<td>IST_v4p017_START_TG65K.med</td>
<td>START</td>
<td>Model startup at full power conditions. Thot = 570°F.</td>
<td>50</td>
<td>495</td>
<td>9.91</td>
<td>63</td>
<td>1.26</td>
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<tr>
<td>Rs1ss_THL_TG65K</td>
<td>Restart 1</td>
<td>Reduce TG speed to 85rpm. CCV4 open from 0.00 to 0.06</td>
<td>400</td>
<td>3006</td>
<td>7.51</td>
<td>358</td>
<td>0.90</td>
<td></td>
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<tr>
<td>Rs2ss_Speed_TG65K</td>
<td>Restart 2</td>
<td>Control switches changed to transition from T/H LEAD to SPEED ctrl</td>
<td>400</td>
<td>3444</td>
<td>8.61</td>
<td>397</td>
<td>0.99</td>
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<tr>
<td>Rs3DP_10pps_MG_TG65K</td>
<td>Restart 3</td>
<td>Down power. Recirculation valve open from 0.00 to 0.59.</td>
<td>400</td>
<td>4126</td>
<td>10.32</td>
<td>461</td>
<td>1.15</td>
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<tr>
<td>Rs4DP_Hdle_CD300_MG_TG65K</td>
<td>Restart 4</td>
<td>TC speed dropped to idle then Thot reduced from 570°F to 300°F.</td>
<td>3700</td>
<td>31300</td>
<td>8.46</td>
<td>3530</td>
<td>0.95</td>
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<tr>
<td>Rs5_CD150_MG_TG65K</td>
<td>Restart 5</td>
<td>Cool down from 300°F to 150°F with TC/TG idle.</td>
<td>3700</td>
<td>33377</td>
<td>9.02</td>
<td>3521</td>
<td>0.95</td>
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<tr>
<td>Rs6CWS_CI_loop_Cidle</td>
<td>Restart 6</td>
<td>Configure CWS to heating mode (isolate inner loop and start Pump1)</td>
<td>400</td>
<td>4777</td>
<td>11.94</td>
<td>510</td>
<td>1.28</td>
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<tr>
<td>Rs7S1S2SD_150F_CWS100F</td>
<td>Restart 7</td>
<td>TC and TG shut down from idle. Turbine inlet T = 150°F.</td>
<td>200</td>
<td>2011</td>
<td>10.05</td>
<td>249</td>
<td>1.24</td>
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<tr>
<td>Rs8S1S2SU_150F</td>
<td>Restart 8</td>
<td>TC and TG start up from 0 rpm. Turbine inlet T = 150°F.</td>
<td>120</td>
<td>1838</td>
<td>16.31</td>
<td>218</td>
<td>1.82</td>
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<tr>
<td>Rs9ILoopSD_150F</td>
<td>Restart 9</td>
<td>CWS inner loop pump ON to OFF. CWS to cooling config</td>
<td>240</td>
<td>3044</td>
<td>12.69</td>
<td>353</td>
<td>1.47</td>
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<tr>
<td>Rs10_WCV3auto_Cidle</td>
<td>Restart 10</td>
<td>Transition to cold idle. Comp inlet temp 100°F. WCV3 in auto.</td>
<td>1400</td>
<td>13694</td>
<td>9.78</td>
<td>1321</td>
<td>0.54</td>
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<tr>
<td>Rs11HU300F_1Hr_TG65Ktab</td>
<td>Restart 11</td>
<td>Brayton loop heated to 300°F from cold idle.</td>
<td>4000</td>
<td>36197</td>
<td>9.05</td>
<td>3790</td>
<td>0.85</td>
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<tr>
<td>Rs12HU435F_1Hr_TG65Ktab</td>
<td>Restart 12</td>
<td>Brayton loop heated to 435°F from 300°F.</td>
<td>4000</td>
<td>34304</td>
<td>8.88</td>
<td>3766</td>
<td>0.85</td>
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<tr>
<td>Rs13HU540F_1Hr_TG65Ktab</td>
<td>Restart 13</td>
<td>Brayton loop heated to 540°F from 435°F.</td>
<td>4000</td>
<td>39875</td>
<td>9.97</td>
<td>3852</td>
<td>0.96</td>
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<tr>
<td>Rs14_TCTG55K_540F_TG65Ktab</td>
<td>Restart 14</td>
<td>Raise TC and TG speeds from idle to 55 krpm.</td>
<td>300</td>
<td>3080</td>
<td>10.27</td>
<td>299</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>
Transient Comparisons: NIST vs. FIT
Summary

- TRACE has been demonstrated as an effective tool for S-CO$_2$ Brayton analysis
  - SNAP GUI/AptPlot enables
    - efficient model building
    - interpretation of results (animation views)
  - predicts loop steady state conditions
  - transient predictions support control system development and operation
  - minimizes risks (trial and error approach) during testing

- High fidelity transient modeling on a PC can approach real time execution by replacing NIST REFPROP with Northland Numerics FIT

- IST transient model still evolving: as-designed $\rightarrow$ as-built $\rightarrow$ as-tested
  - Update performance maps
  - Update windage correlation
  - Update component performance (e.g. valve $C_{SUBV}$, Hx’s dP)

- Future: complete qualification of TRACE code for use as an effective tool for scale-up designs