Comparison of Analytical Predictions and Experimental Results for a Dual Brayton Power System

(Discussion on Test Hardware and Computer Model for a Dual Brayton System)

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Abstract. NASA Glenn Research Center (GRC) contracted Barber-Nichols, Arvada, CO to construct a dual Brayton power conversion system for use as a hardware proof of concept and to validate results from a computational code known as the Closed Cycle System Simulation (CCSS). Initial checkout tests were performed at Barber-Nichols to ready the system for delivery to GRC. This presentation describes the system hardware components and lists the types of checkout tests performed along with a couple issues encountered while conducting the tests. A description of the CCSS model is also presented. The checkout tests did not focus on generating data, therefore, no test data or model analyses are presented.
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Introduction

- Recent attention given to gas cooled reactors for potential space power applications
  - No existing hardware to evaluate effect of redundant power conversion units coupled to a gas reactor
  - Experimental studies deemed critical to proof of concept
  - NASA Glenn Research Center contracted for system design and fabrication with Barber-Nichols, Arvada, CO
- A single CBC test loop very similar to this system already exists
  - Also built by Barber-Nichols
  - Resides at Sandia National Laboratories (SNL) and tested by Dr. Stephen A. Wright
- The dual system is unique because it employs two CBC units sharing a common gas inventory and common heat source
  - Working fluid free to redistribute between the two CBC loops as system operation dictates
  - Hardware not flight-like, but sufficient for demonstrating the proof of concept
- Operational areas of interest
  - CBC units at different shaft speeds
  - One CBC unit while the other is standby (i.e. it is off)
  - Starting the CBC units in both staggered and simultaneous fashion
- Parallel computer model development done in Closed Cycle System Simulation (CCSS) design and analysis tool
  - Will be used for pretest predictions and posttest validation
  - Can be employed to make informed decisions for designing future systems
Dual Brayton System

- Recup. Low Pressure Exhaust
- Flow Orifice
- Bellows
- Recup. High Pressure Exhaust Plenums
- Cooler
- Heater
- Flex Hoses
- Check Valves
- Alternator, Compressor, Recuperator, Turbine
- Flow Splitter to Turbine Inlet

Glenn Research Center at Lewis Field
Modified Capstone C-30

• Centered the design around a modified Capstone Model C-30 commercial microturbine
  – 30 kWe, air-breathing converter
  – Comprises alternator, compressor, recuperator, and turbine
  – Added 4 ducts from recuperator high pressure exit to heater inlet
  – Added 6 ducts from heater exit to turbine inlet
Gas Cooler

- Basco/Whitlock gas-to-liquid heat exchanger
- Shell and tube design
  - Gas flows through 70, 0.5 in. I.D. tubes
  - Water flows through shell side, 8.0 inch I.D.
  - 114 inches long (9.5 ft)
Heater

- Only component shared by the two Brayton loops
- Chromalox – custom built, 180 kW-rated electric resistance heater
  - Maximum achievable gas temperature of 1000 K (Capstones designed for 1144 K)
- Similar to that of a shell and tube heat exchanger
  - 48 heating elements (Incoloy 800) act as the tube portion, 0.475 in. O.D.
  - Series of baffles persuades the gas working fluid across the tubes in the shell portion, 7.98 in. I.D.
  - ~ 300 inches long (25 ft)
- Anticipated 2-3 psi pressure drop at design speed
Assembled Hardware

- The modified Capstone C-30 units, gas coolers, and heater were assembled to form the dual Brayton test loop
- The entire system is 19 feet long, 10 feet wide, and 8 feet high
System Operation

- Operation requires only a few user control inputs
  - Heat input, heat rejection, and an electric load
- Heater set to maintain a specific power or exit temperature
  - Only one turbine inlet temperature is allowed – one heater
- Waste heat is rejected to the facility water running through the gas cooler
  - Supply temperature is relatively constant for a given day
  - Manual valve is used to control the flow rate of the water
- Retained the Capstone commercial controller, which uses a parasitic load to maintain a set shaft speed
- Computer interface sends command signals to a central controller which communicates with Capstone and heater controllers
- Each CBC loop can be operated at different shaft speed set points
- Certain safeguards in place
  - Capstone controller will not let the shaft over speed
  - Burst disc on each Brayton loop in case of over pressure
  - Heater controller monitors sheath material temperature
  - On-screen warning if compressor inlet pressure is low
  - System shutdown if coolant flow is lost
Computer Model

• Closed Cycle System Simulation (CCSS)
  – Numerical Propulsion System Simulation (NPSS) environment
  – Used previously in analytical studies and test hardware performance studies
  – Modeled a flight-like, 2kW Brayton power conversion unit tested at NASA GRC
• Operated in three separate modes: design, off-design, and transient
  – Design
    • Hardware geometries are known and coded into the model setup
  – Off-design
    • Steady-state solutions
    • Vary shaft speed, heater power, turbine inlet temperature, coolant flow rate, gas inventory, etc.
  – Transient
    • Material temperatures become time-dependent
    • Turbomachinery is assumed to operate in a quasi-steady-state mode
• Solver handles 177 independent variables
  – Most of the variables are hardware material temperatures
  – Drive the system to equilibrium
    • All heat transferred is accounted for
    • Sum of the pressure drops/rises around the loop must be zero
    • System gas inventory distributed as necessary
Turbine and Compressor Models

- Compressor performance map generated in CCODP (Centrifugal Compressor Off-Design Program)
  - 10 to 105% design speed
- Turbine performance map generated in RTOD (Radial Turbine Off-Design) program
  - 10 to 155% design speed
Recuperator Model

- Gas-to-gas, offset strip-fin, counter flow heat exchanger ~ 78% effective
- Kays and London heat transfer and friction factor coefficients
- Structure is divided into ten nodes – stainless steel
- Heat loss across the insulation is always calculated as steady-state

\[
\dot{Q} = h_c A (T_{\text{mat}} - T_{\text{fluid}})
\]

\[
\frac{dT_{\text{mat}}}{dt} = \frac{Q_{\text{in}} - Q_{\text{out}}}{m_{\text{mat}} C_{\text{mat}}}
\]
Gas Cooler Model

- Shell-and-Tube, gas-to-water heat exchanger
- Circular pipe flow correlations for heat transfer and friction factor coefficients
- Structure is divided into ten nodes – stainless steel tubes, carbon steel shell
- Heat loss to ambient air, but no insulation
Electric Heater Model

- Shell-and-Tube like electric resistance gas heater
- Modified circular pipe flow correlations for heat transfer and friction factor coefficients
- Structure is divided into forty nodes – Incoloy 800 heating elements, stainless steel shell
- Heat loss across the insulation is always calculated as steady-state
Status

• Checkout tests performed at Barber-Nichols
  – Individual units ran as single loop with second unit blanked
  – Staggered and simultaneous dual system startups
  – Ran dual system at equal and unequal speeds
  – Heater power limited at Barber-Nichols facility

• Current issues with system hardware
  – Internal flow leakage in the Capstone units
    • Recuperator HP exit to turbine inlet/exit
    • Recuperator bypass flow at housing
    • Resolved through installation of internal manifold
  – Heater pressure drop much greater than design specification
    • Anticipated 2-3 psi drop, measured >3 psi at half speed, estimate >10 psi at full speed
    • Working with Chromalox to resolve the issue
    • Proposed solution to reduce number of internal baffles

• Expected delivery to Glenn early Spring
Conclusions

• Built a dual closed-Brayton-cycle system with common heat source and common working fluid
• Demonstrated the ability to startup and shutdown units independently
• Demonstrated operation with speed imbalance
• Need to resolve heater pressure drop issue
• Will compare test data to model analysis