Design and Off-Design Performance of 100 kWe-Class Brayton Power Conversion Systems

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The NASA Glenn Research Center in-house computer model *Closed Cycle Engine Program (CCEP)* was used to explore the design trade space and off-design performance characteristics of 100 kWe-class recuperated Closed Brayton Cycle (CBC) power conversion systems. Input variables for a potential design point included number of operating units (1, 2, 4), working-fluid molecular weight (20, 40, 80 g/mol), and turbo-alternator shaft speed (30, 45, 60 kRPM). The design point analysis assumed a fixed turbine inlet temperature (1150 K), compressor inlet temperature (400 K), peak cycle pressure (1 MPa), compressor pressure ratio (2.0), and recuperator effectiveness (0.95), and a Sodium-Potassium (NaK) pumped-loop radiator. The design point options were compared on the basis of thermal input power, radiator area, and mass. For a nominal design point with fixed Brayton components and radiator area, off-design cases were examined by reducing turbine inlet temperature (as low as 900 K), reducing shaft speed (as low as 50% of nominal), and considering several component by-pass flow arrangements. The off-design analysis was focused on approaches to reduce thermal input power without freezing the radiator.
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Abstract. The NASA Glenn Research Center in-house computer model Closed Cycle Engine Program (CCEP) was used to explore the design trade space and off-design performance characteristics of 100 kWe-class recuperated Closed Brayton Cycle (CBC) power conversion systems. Input variables for a potential design point included the number of operating units (1, 2, 4), cycle peak pressure (0.5, 1, 2 MPa), and turbo-alternator shaft speed (30, 45, 60 kRPM). The design point analysis assumed a fixed turbine inlet temperature (1150 K), compressor inlet temperature (400 K), working-fluid molecular weight (40 g/mol), compressor pressure ratio (2.0), recuperator effectiveness (0.95), and a Sodium-Potassium (NaK) pumped-loop radiator. The design point options were compared on the basis of thermal input power, radiator area, and mass. For a nominal design point with defined Brayton components and radiator area, off-design cases were examined by reducing turbine inlet temperature (as low as 900 K), reducing shaft speed (as low as 50% of nominal), and circulating a percentage (up to 20%) of the compressor exit flow back to the gas cooler. The off-design examination sought approaches to reduce thermal input power without freezing the radiator.
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Outline

• Introduction
• Conceptual design methodology
• Method description
• Model description
• Design case definition
• Design case results
• Off-Design case definition
• Off-Design case results
• Conclusions

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Introduction

• Closed-Brayton-cycle (CBC) is a candidate thermodynamic cycle for a 100 kWe-class Jupiter Icy Moons Orbiter (JIMO) type spacecraft

• CBC space power conversion systems (PCS) must be designed to minimize thermal input power, converter mass, and heat rejection system (HRS) radiator area
  – Chose to vary three design parameters: shaft speed, cycle peak pressure, and number of CBC units

• Off-design operation for an extended period of time could extend reactor life by reducing the thermal power requirement and/or peak operating temperature
  – Chose to reduce turbine inlet temperature, shaft speed, and mass flow rate through the turbine (by circulating a percentage of compressor exit flow back to the gas cooler)
Method

• In-house code Closed Cycle Engine Program (CCEP)
  – Design and off-design performance analysis and mass estimates
  – Single-stage, radial turbomachinery design tables
  – Bearing and windage losses based on alternator power and cycle peak pressure
  – Kays and London based recuperator and gas cooler
  – Gas ducting
  – Pumped-loop radiator
  – Solar collector or nuclear heat source
• Majority of design variables are identical for all design cases
  – Turbine inlet temperature (TIT), compressor inlet temperature (CIT) compressor pressure ratio (CPR), working-fluid composition, alternator power, radiator far-field temperature, heat exchanger effectiveness, relative pressure drop across the components
• Vary only select variables during design
  – Combinations of cycle peak pressure, shaft speed, and number of CBC units/engines
• One design-point is selected for the transition to off-design
  – Hardware geometries and gas inventory are fixed
  – Vary one off-design variable at a time
    • Shaft speed, turbine inlet temperature, and compressor exit flow recirculation
  – Map scaling technique used for off-design turbine and compressor performance
Model Description

- Design-point constants
  - TIT: 1150 K
  - CIT: 400 K
  - Compressor pressure ratio: 2.0
  - Working-fluid composition: He-Xe 40 g/mol
  - Total output power: 100 kWe
  - Radiator far-field temperature: 200 K
  - Radiator pressure drop: 0.14 MPa (20 PSI)
  - Recuperator
    - Effectiveness: 95%
    - Hot-side relative pressure drop: 1.5%
  - Gas cooler effectiveness: 97%
  - Relative pressure drop for each gas duct: 0.20 %
  - Heat source heat exchanger relative pressure drop: 2.7%
- Radiator is pumped-loop configuration with NaK-78 coolant pumped by an Annular Linear Induction Pump (ALIP)
  - Separate NaK loop and ALIP pump for each CBC converter
- Recuperator and gas cooler are counter flow, offset strip fin
- Duct wall thicknesses sized for 100,000 hours of creep stress, 2.0 factor of safety
Design Case Definition

- Varied three design parameters
  - Shaft speed (30000, 45000, 60000 RPM)
  - Cycle peak pressure (0.5, 1.0, 2.0 MPa)
  - Number of CBC units (1 at 100kWe, 2 at 50kWe, 4 at 25kWe)
- Compared on basis of CBC mass (recuperator, gas cooler, turbine-alternator-compressor, and ducting), thermal input power, and radiator area (two-sided)
- Total of 22 converged cases examined

Converged Cases for 1, 2, and 4 CBC units

<table>
<thead>
<tr>
<th>RPM</th>
<th>Peak Pressure (MPa)</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
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<tr>
<td>30000</td>
<td>1, 2</td>
<td>1, 2</td>
<td>1, 2</td>
<td>1, 2, 4</td>
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<tr>
<td>45000</td>
<td>1, 2</td>
<td>1, 2</td>
<td>1, 2</td>
<td>1, 2, 4</td>
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<tr>
<td>60000</td>
<td>1</td>
<td>1</td>
<td>1, 2</td>
<td>1, 2, 4</td>
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Design Results at 45000 RPM

CBC Mass (kg)

0 200 400 600 800 1000 1200 1400

Cycle Peak Pressure (MPa)

0 0.5 1 1.5 2 2.5

N = 45000 RPM

Required Heat Input (kW)

0 100 200 300 400 500 600 700

Cycle Peak Pressure (MPa)

0 0.5 1 1.5 2 2.5

N = 45000 RPM

Radiator Area (m²)

0 50 100 150 200 250 300

Cycle Peak Pressure (MPa)

0 0.5 1 1.5 2 2.5

N = 45000 RPM

4 Units

2 Units

1 Unit

4 Units

2 Units

1 Unit

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Design Results at 2.0 MPa

- CBC Mass (kg)
  - Shaft Speed, $N$ (RPM)
  - $P_{peak} = 2$ MPa
  - 4 Units
  - 2 Units
  - 1 Unit

- Required Heat Input (kW)
  - Shaft Speed, $N$ (RPM)
  - $P_{peak} = 2$ MPa
  - 4 Units
  - 2 Units
  - 1 Unit

- Radiator Area (m²)
  - Shaft Speed, $N$ (RPM)
  - $P_{peak} = 2$ MPa
  - 4 Units
  - 2 Units
  - 1 Unit

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## Minimum Cases

<table>
<thead>
<tr>
<th>Minimum Case</th>
<th># Units</th>
<th>Mass (kg)</th>
<th>$Q_{HeXe}$ (kWt)</th>
<th>$A_{Rad}$ (m$^2$)</th>
<th>$P_{peak}$ (MPa)</th>
<th>$N$ (RPM)</th>
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<tbody>
<tr>
<td>CBC Mass</td>
<td>1</td>
<td>580</td>
<td>426</td>
<td>165</td>
<td>2</td>
<td>60000</td>
</tr>
<tr>
<td>Radiator Area</td>
<td>1</td>
<td>656</td>
<td>398</td>
<td>155</td>
<td>1</td>
<td>45000</td>
</tr>
<tr>
<td>Heat Input</td>
<td>2</td>
<td>890</td>
<td>393</td>
<td>158</td>
<td>0.5</td>
<td>45000</td>
</tr>
</tbody>
</table>

- Resulting combination of performances among components
  - Recuperator mass (30 – 50% of CBC mass) decreases with increased pressure
  - Duct wall thicknesses increase with increased pressure
  - Bearing and windage losses increase with increased pressure
  - Turbomachinery efficiencies decrease with increased pressure, but increase with increased shaft speed
  - Turbine-alternator-compressor mass decreases at higher shaft speeds

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Off-Design Case Definition

• Nominal Design Point:
  – 45000 RPM shaft speed
  – 1.0 MPa cycle peak pressure
  – Two 50 kWe Brayton units
  – Geometries and gas inventory fixed for the transition to off-design

• Varied three operating parameters, one at a time
  – Shaft speed (100 – 50%)
  – Turbine inlet temperature (1150 – 900 K)
  – Compressor exit flow circulation (0 – 20%)

• Reduce thermal input power without freezing the radiator
  – Radiator far-field temperature maintained at 200 K
  – $T_{\text{NaK}} > 262$ K
  – NaK mass flow rate kept constant

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Off-Design Nominal Operating Point

- NaK 1.33 kg/s
- 1.40 kg/s
- HRS string #2 operating at same state-point conditions

- ALIP Pump
- 334 kWt
- Main Radiator
- $T_{R_{\text{Ref}}} = 175 \text{ m}^2$
- $T_{\text{SW}} = 200 \text{ K}$
- 523 K

- Gas Cooler
- 160 kWt
- 97%
- 0% Circulation, $\lambda$
- 581 K
- 1.00 MPa
- 0.502 MPa

- Comp.
- 474 K
- 82.2%
- 1.71 kg/s
- 0.500 MPa
- CPR 2.00
- $N = 45 \text{ kRPM}$
- TIT/CIT = 2.86
- Cyc Eff = 23.2%

- Turbo-Alternator
- 50.0 kWt
- 94%
- 922 K
- 0.511 MPa
- TPR 1.89

- Turc.
- 1150 K
- 0.964 MPa
- 215 kWt

- Heat Source Exchanger
- He-Xe 1.67 kg/s
- 40.0 g/mol

- Main Radiator
- 301 kWt
- Recuperator
- 95%
- 902 K
- 0.993 MPa

- Q_{He-Xe} = 431 kWt

- CBC string #2 operating at same state-point conditions

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Off-Design Performance Results

Shaft Speed (% of Design Speed)

T_{Cold,NaK (K)}
Q_{HeXe (kWt)}
W_{Al (kWe)}

T_{Cold,NaK (K)}
Q_{HeXe (kWt)}
W_{Al (kWe)}

Circulated Compressor Exit Flow (%)

T_{Cold,NaK (K)}
Q_{HeXe (kWt)}
W_{Al (kWe)}

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Conclusions

• Design point conclusions
  – The one-Brayton-unit system always exhibited lower mass, radiator area, and thermal input power than the two-unit and four-unit power conversion systems
  – Lower cycle peak pressure resulted in a smaller radiator and less thermal input power
    • Mass not as sensitive to cycle peak pressure over the range of 0.5 – 2.0 MPa
  – Higher shaft speeds resulted in lower Brayton mass, smaller radiator area, and less thermal input power
  – Suggested improvements to the method
    • Use a bearing and windage loss model that accounts for shaft speed. We do have a physics-based model, but it is believed to have high uncertainty. Experiments are underway at GRC

• Off-design performance conclusions
  – Reducing the shaft speed was most effective at reducing thermal input power, but also lowered the NaK temperature the most and changes alternator frequency
  – Lowering the turbine inlet temperature was next most effective at reducing thermal input power, NaK temperature dropped very little
  – Circulating compressor exit flow was least effective at reducing thermal input power, NaK temperature actually increased slightly
  – Of the cases considered, probably a combination of reduced shaft speed and lowered turbine inlet temperature would be most effective at extending reactor life as well as slowing secondary creep in the hot-end materials
  – Suggested improvements to the method
    • Examine combinations of off-design operating points
    • Look at the effects of changing the gas inventory

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Backup Charts
Design Results at 30000 RPM

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Design Results at 45000 RPM

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Design Results at 60000 RPM

- CBC Mass (kg)
  - 4 Units
  - 2 Units
  - 1 Unit

- Required Heat Input (kW)
  - 4 Units
  - 2 Units
  - 1 Unit

- Radiator Area (m²)
  - 4 Units
  - 2 Units
  - 1 Unit

N = 60000 RPM

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Design Results at 0.5 MPa

CBC Mass (kg)

Shaft Speed, N (RPM)

Required Heat Input (kW)

Shaft Speed, N (RPM)

Radiator Area (m²)

Shaft Speed, N (RPM)
Design Results at 1.0 MPa

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Design Results at 2.0 MPa

- CBC Mass (kg)
- Required Heat Input (kW)
- Radiator Area (m²)

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