Mass Modeling of NEP Power Conversion Concepts for Human Mars Exploration

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Agenda

• Introduction

• Performance Model

• Mass Model Formulation
  - Reactor
  - Turboalternator
  - Heat Rejection
  - Ducting
  - PMAD

• Results
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  - Optimization
    - Radiator Pressure Drop
    - Compressor Inlet Temperature
  - General Trends
  - Conclusions
NEP is under consideration by NASA as propulsion for a crewed Mars mission

- A MW-class (2-4 MW\textsubscript{e}) NEP system is needed
- 5 critical technology elements (CTEs)
  - Reactor system (RXS)
  - Power conversion system (PCS)
  - Power management and distribution (PMAD)
  - Electric propulsion system (EPS)
  - Primary heat rejection system (PHRS)
- The goal of this work is to inform NEP technology development and down selection
  - Illustrate the impact of technology performance on system level KPP
  - Number and type of working fluids
  - Optimize design variables
- One of the most important variables is the power system specific mass, $\alpha_{ps}$
  - Defined as the mass of RXS, PCS, PMAD and PHRS, in kg, per kilowatt of electrical power output to EPS
The mass model works in conjunction with the performance model

- Performance model solves thermodynamics
  - Chris Harnack will present *Brayton Cycle Power Conversion Model for MW-Class Nuclear Electric Propulsion Mars Missions* in the NEP II session on Thursday
  - Cycle efficiency
  - Mass flow rate
  - Radiator area
  - Temperature and pressure state points

- Output values used to estimate the mass for the NEP system components

- Uncertainty in performance model assumptions
  - Low TRL of the components
  - Leads to uncertainty in system mass estimates
  - Current and Future Work is to increase fidelity of mass and performance models

<table>
<thead>
<tr>
<th>Performance Model Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power level</td>
<td>2 MWₑ, 4 MWₑ</td>
</tr>
<tr>
<td>Turbine inlet temperature</td>
<td>1200 K, 1400 K</td>
</tr>
<tr>
<td>He-Xe ratio</td>
<td>72 wt% He</td>
</tr>
<tr>
<td>Turbine inlet pressure</td>
<td>2 MPa</td>
</tr>
<tr>
<td>Turbine efficiency</td>
<td>0.89</td>
</tr>
<tr>
<td>Compressor efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>Radiator emissivity</td>
<td>0.9</td>
</tr>
<tr>
<td>Radiator view factor</td>
<td>0.85</td>
</tr>
<tr>
<td>Radiator sink temperature</td>
<td>4 K</td>
</tr>
<tr>
<td>Recuperator effectiveness</td>
<td>0.9</td>
</tr>
<tr>
<td>Reactor HX effectiveness</td>
<td>0.9</td>
</tr>
<tr>
<td>Radiator HX effectiveness</td>
<td>0.9</td>
</tr>
<tr>
<td>Compressor inlet temperature</td>
<td>Optimized</td>
</tr>
<tr>
<td>Radiator pressure drop</td>
<td>Optimized</td>
</tr>
</tbody>
</table>

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Nuclear and Emerging Technologies for Space (NETS) Conference 2022
Mass Model Formulations

Reactor and Shield

• Coupled thermal hydraulic and neutronic models used to converge on reactor outlet temperature
• Unit cells are added until reactor power level is reached
  • Mass of each unit cell is precalculated
• Constant thickness radial and axial reflector
• Pressure vessel sized using hoop stress
• Additional subcomponents modeled using RSMASS-D correlations
  • SP-100 project reactor concepts
• Tungsten used for the gamma shield and lithium hydride for the neutron shield
Mass Model Formulations

**Turboalternator**

- Anchored by the turboalternator used in the Brayton Rotating Unit
- Turbomachine diameter calculated using a higher fidelity version of the performance model
- *Nuclear Electric Propulsion Modular Power Conversion Model* to be presented by Dennis Nikitaev in the NEP II session on Thursday
- The BRU geometry is scaled linearly up with the diameter
- Process was completed for a variety of operating conditions
- Correlation was developed to calculate turboalternator $\alpha$ as a function of electric power output

$$\alpha_{Turbo,He-Xe} = 1.37Power^{-0.2196}$$
Mass Model Formulations

Heat Exchangers

- Scaled from JIMO (Ref. 11) and SDB SSF (Ref. 12)
  - Operating conditions and volume/mass are known
    - Linear scaling between these two data points
  - Assume density of heat exchanger is proportional to pressure
    - Represents the thickness of the tubes needed
  - Assume the volume of the heat exchanger is proportional to the mass flow rate
    - Represents the number of tubes needed to accommodate the flow
- Sunden\(^3\) used to scale heat exchanger mass based on effectiveness
  \[ SV = 8.1E - 5 \times \exp(15.8 \times \epsilon) \]
  - SV is the specific volume (cm\(^3\)/kg/s) and is scaled by

<table>
<thead>
<tr>
<th></th>
<th>JIMO</th>
<th>SDB SSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>m(_\text{dot}) Brayton</td>
<td>3.73 kg/s</td>
<td>1.15 kg/s</td>
</tr>
<tr>
<td>Volume Recuperator</td>
<td>0.7 m(^3)</td>
<td>0.3 m(^3)</td>
</tr>
<tr>
<td>High pressure into</td>
<td>1.38 MPa</td>
<td>0.543 MPa</td>
</tr>
<tr>
<td>Recuperator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass of the Recuperator</td>
<td>486 kg</td>
<td>162 kg</td>
</tr>
<tr>
<td>Volume Radiator HX</td>
<td>0.2 m(^3)</td>
<td>0.08 m(^3)</td>
</tr>
<tr>
<td>High pressure into</td>
<td>0.7 MPa</td>
<td>2.96 MPa</td>
</tr>
<tr>
<td>Radiator HX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass of the Radiator HX</td>
<td>355 kg</td>
<td>85 kg</td>
</tr>
</tbody>
</table>
Mass Model Formulations

Heat Rejection

- Work done by Siamidis\textsuperscript{14} provided a starting point
  - Needed to be made parametric
- The diameter of the ducting is sized to satisfy a radiator pressure drop requirement
  - Ducting mass is inversely proportional to pressure drop
- Carbon fiber panel thickness calculated using fin efficiency equations
- The support structure is scaled from FEA work done on the central truss by the NASA Advanced Concepts Office (ACO) and Aerojet\textsuperscript{16}
Mass Model Formulations

**Ducting, Pump and Accumulator**

- The ducting diameter is sized to accommodate the mass flow with a 1% pressure drop between the RXS and PCS and a 2% drop within the PCS.
- Length of ducting estimated using conceptual layout of the NEP system.
- A specific mass of 250 kg per kW of required pump power is used.
  - Very conservative estimate of the pump mass – significant decreases can be expected with future technology development.
- Accumulator mass scaled using the volume differential in the fluid at launch and operational temperature.
  - Accumulator designs from Tournier and El-Genk used as a basis.

[Diagram of NEP system components: Reactor HX, Radiator HX, Recuperators, Turbomachines, Shield, Reactor]
The mass of the PMAD electronics is calculated using the $\alpha$ vs power relationship shown in Frisbee\textsuperscript{17}

$$\alpha_{PMAD} = 128.63 \times \text{Power}^{-0.502}$$

Two additional components are also accounted for in the PMAD mass
- PMAD radiator – rejects waste heat generated by PMAD electronics (96% efficiency)
  - 7 kg/m$^2$, 400 K
- Parasitic load radiator – dissipates electric power not being used by EPS
  - 10 kg/m$^2$, 850 K
Increasing mass flow rate leads to increased radiator areal density

- Ducting diameter need to increase to accommodate higher flow rates
  - Becomes unreasonably large
  - Duct size limited after 30 kg/s (assuming parallel loops)
- Triple loop configuration has a much lower mass flow rate
  - Higher specific heat of NaK compared to He-Xe
  - Allows for lower areal density in triple loop case despite very conservative pump mass
There is an optimum radiator pressure loss for each NEP power system configuration

- Radiator pressure drop is the most important variable to determine radiator areal mass

- Higher pressure loss leads to
  - Smaller ducting and lower radiator areal mass
  - Lower cycle efficiency

- Decrease in efficiency is much larger in the single loop configuration
  - Compressor must account for the pressure loss
  - For the triple loop configuration, the pump can make up this pressure loss much more efficiently
    - Higher optimum pressure drop for triple loop configuration
The optimal compressor inlet temperature is lower if \( \alpha \) is optimized than if radiator area is optimized

- Higher compressor outlet temperature leads to
  - Higher radiative power per area
  - But a less efficient cycle
- The radiative power is proportional to \( T^4 \)
  - Drives the radiator area trend when just the cycle thermodynamics are considered
  - The effect of the less efficient cycle becomes more important when mass is considered
- Less efficient cycles will require more mass flow rate
  - Leads to increased mass of all the components
    - In particular, the radiator will become significantly heavier due to larger ducting requirements
General Trends

- $\alpha_{ps}$ decreases at higher power levels
  - Most components are more mass efficient at higher power
  - Diminishing returns

- Much lower $\alpha_{ps}$ obtained by increasing the turbine inlet temperature
  - Allows for both a higher efficiency and higher effective radiating temperature
  - Thermal limits of material are the limiting factor

- Single loop configuration may have lower $\alpha_{ps}$ despite lighter radiators in triple loop
  - Lower efficiency
    - Temperature losses across heat exchangers
  - Additional equipment in triple loop
    - Heat exchangers, pumps, and accumulators
  - This gap is relatively small and may close as the models are improved
Conclusions

• Model predicts mass based on system performance parameters
• Increasing the turbine inlet temperature has a large positive impact on $\alpha_{ps}$
• Optimizing for radiator area is not the same as optimizing for mass
  - NEP system should be designed within these bounds (compressor inlet temperature between minimum radiator area and minimum $\alpha_{ps}$)
• Increasing power level will reduce $\alpha_{ps}$
  - High power may not be beneficial due to diminishing returns and a higher Earth departure mass
• The single loop configuration may have lower mass than the triple loop
  - The triple loop configuration has other advantages
• This mass model is intended to demonstrate trends within the design space, not prescribe a particular design choice
  - Exact numbers and their relative magnitudes are expected to change as the technology maturation effort continues, hardware is developed, and better validation and assumptions become available
References


