Comparison of Green and Conventional Rocket Propellants: System Analysis Tool for in-space Propulsion

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Motivation
Comparison of different propellants

• Global research activities on various green propellants

• Comparison often based solely on $I_{sp}$

• But:
  • Propellant density effects the performance of the overall system
  • Different propulsion system designs can offer additional advantages
Motivation
Comparison of different propellants

• “Best” propellant choice influenced by spacecraft size/mass and Δv budget

• Performance parameters of existing thrusters are known

• For lower TRL systems often only the theoretical performance is known

Aim:
• Assess and compare the performance of different green propellants to conventional propellants on a system level
• Comparison of system mass and Δv
Background and assumptions

- Propellant and propulsion system data from literature [8-41], see reference list
- Performance based on experimental literature data, otherwise CEA calculations with adjustable efficiency losses
- Self-pressurization: No mass for pressurant tank, pressurant piping, pressurant valves and pressurant needed
- All tanks are spherical
- Calculation of tank thickness/mass with Barlow’s formula depending on tank/propellant pressure
- Thruster masses based on existing mono- and bipropellant thrusters, system component’s masses based on existing systems
- HyNOx thrusters have 50% more mass compared to non-HyNOx thrusters
Calculation steps

\[ \Delta v = I_{sp} g_0 \ln \left( \frac{m_{sc\, dry} + m_{tanks} + m_{propellant} + m_{pressurant} + m_{prop\, sys}}{m_{sc\, dry} + m_{tanks} + m_{prop\, sys}} \right) \]

Spacecraft Dry Mass

Volume of propellant tank

Selection of propellant and efficiency

Number of propellant and pressurant tanks

Calculation of Tank, Pressurant mass

Calculation of propulsion system dry mass

Calculation of \( \Delta v \)

Calculation of \( \Delta v \) for increase of propellant, pressurant and tank mass

Mass of propulsion system without tanks

For specific conditions

Plotting: Spacecraft Mass vs. \( \Delta v \)
**Calculation steps**

1. **Mass without propulsion system**
   - \( \Delta v = I_{sp} g_0 \ln \left( \frac{m_{sc \ dry} + m_{\text{tanks}} + m_{\text{propellant}} + m_{\text{pressurant}} + m_{\text{prop sys}}}{m_{sc \ dry} + m_{\text{tanks}} + m_{\text{prop sys}}} \right) \)

2. **Volume of propellant tank**

3. **Selection of propellant and efficiency**

4. **Number of thrusters, propellant and pressurant tanks**

5. **Calculation of Tank and Pressurant masses**

6. **Calculation of propulsion system dry mass**

7. **Calculation of \( \Delta v \)**

8. **Calculation of \( \Delta v \) for increase of propellant, pressurant and tank mass**

9. **For specific conditions**

10. **Plotting: Spacecraft Mass vs. \( \Delta v \)**
Propellants included

**Monopropellants:**
- N₂H₄
- LMP-103S
- FLP-106
- H₂O₂
- EUFB (Europen Fuel Blend, premixed N₂O/EtOH)
- HyNOx (DLR premixed N₂O/C₂H₆)
  - Self-pressurized
  - External pressurization
- AF-M315E
- SHP 163

**Bipropellants:**
- MMH/NTO
- HIP_11 (DLR Hypergolic Bipropellant)
- HyNOx (DLR non-premixed N₂O/C₂H₆)
  - Self-pressurized
  - External pressurization
Propellants included

**Generic propellants:**

- Monopropellant, user input:
  - $I_{sp}$
  - Density
  - Self pressurized: Pressure inside the tank

- Bipropellant, user input:
  - $I_{sp}$
  - Oxidizer to fuel ratio
  - Density of oxidizer and fuel
  - Self pressurized: Pressure inside the tanks
User Interface:

- **Spacecraft Dry Mass**
- **Propellant selection**
- **Number of tanks**
- **Propellant Tank Volume**
- **Efficiency**
- **Number of Thrusters**
- **Results for the given conditions**
- **Plot spacecraft mass vs. Δv**

### Comparison using Spacecraft Dry Mass and Tank Volume

<table>
<thead>
<tr>
<th>Spacecraft Dry Mass (kg)</th>
<th>Propellant Tank Volume (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>250</strong></td>
<td><strong>46</strong></td>
</tr>
</tbody>
</table>

**Existing Propellants**

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 C2H6/N2O4</td>
<td>100</td>
</tr>
<tr>
<td>2 N2H4/CH4</td>
<td>100</td>
</tr>
</tbody>
</table>

**Propellant selection**

<table>
<thead>
<tr>
<th>Number of Thrusters</th>
<th>22, 200, 400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nr. 22 N Thrusters</td>
<td>8</td>
</tr>
<tr>
<td>Nr. 200 N Thrusters</td>
<td>0</td>
</tr>
<tr>
<td>Nr. 400 N Thrusters</td>
<td>1</td>
</tr>
</tbody>
</table>

**Results for the given conditions**

<table>
<thead>
<tr>
<th>Spacecraft Wet Mass 1 (kg)</th>
<th>Δv</th>
<th>Mass Propellant 1 (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>309.1</td>
<td>300</td>
<td>300.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spacecraft Wet Mass 2 (kg)</th>
<th>Δv</th>
<th>Mass Propellant 2 (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>333.8</td>
<td>504</td>
<td>504.2</td>
</tr>
</tbody>
</table>
Exemplary results

Comparison of mono- and bipropellant systems for 250 and 500 kg spacecraft dry mass

- For high $\Delta v$ requirements the higher $I_{sp}$ of bipropellant systems exceeds the drawbacks of higher system weights
- Pure monopropellant system results in lower spacecraft mass for
  - 250 kg spacecraft when up to 230 m/s $\Delta v$ are needed
  - 500 kg spacecraft when up to 120 m/s $\Delta v$ are needed
- For lower spacecraft masses, the lower masses of $N_2H_4$ systems are more advantageous

<table>
<thead>
<tr>
<th></th>
<th>Hydrazine</th>
<th></th>
<th>NTO/MMH</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{sp}$</td>
<td>230</td>
<td>320</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>60</td>
<td>330</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eff.%</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Increasing propellant (and tank) mass

Overall spacecraft mass [kg]

Overall spacecraft mass [kg]
**Exemplary results**

<table>
<thead>
<tr>
<th>Hydrazine</th>
<th>Eff.</th>
<th>LMP-103S</th>
<th>Eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$I_{sp}$</td>
<td>$\epsilon$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>230</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>253</td>
<td>150</td>
</tr>
</tbody>
</table>

Comparison of conventional and green mono-propellant systems for 250 kg spacecraft dry mass

- Due to the higher $I_{sp}$ and density of LMP-103S additional $\Delta v$ can be gained for the same spacecraft mass
  - For e.g. 350 kg overall mass the $\Delta v$ gain is 70 m/s (605 vs. 675 m/s)
Exemplary results

Comparison of conventional and green monopropellant systems for 250 kg spacecraft dry mass

- Up to a $\Delta v$ of 585 m/s HyNOx beneficial due to lower system mass – no external pressurization needed
- Above $\Delta v$ of 585 m/s higher $\Delta v$ available with conventional NTO/MMH
- HIP_11 as hypergolic green propellant is suitable for higher $\Delta v$ requirements, despite slightly lower performance than conventional NTO/MMH
Exemplary results

Comparison of conventional and green mono-propellant systems for 1000 kg spacecraft dry mass

- Up to a Δv of 160 m/s HyNOx beneficial due to lower system mass – no external pressurization needed
- Due to lower $I_{sp}$ of HyNOx, lower density and higher tank pressures above 160 m/s HIP 11 or NTO/MMH is advantageous
- HIP_11 as hypergolic green propellant is suitable for higher Δv requirements, despite slightly lower performance than conventional NTO/MMH

<table>
<thead>
<tr>
<th>NTO/MMH</th>
<th>HIP_11</th>
<th>HyNOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{sp}$</td>
<td>ε</td>
<td>$I_{sp}$</td>
</tr>
<tr>
<td>320</td>
<td>330</td>
<td>316</td>
</tr>
<tr>
<td>Eff.%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Summary

- Basic comparison tool for different conventional and green propellants developed
- Tool takes spacecraft mass, propulsion system mass, tank masses, propellant, pressurant and thruster masses into account
- A specific propellant can be selected or a generic propellant can be defined
- $I_{sp}$ efficiency, number of tanks (propellant, pressurant), number and size of thrusters can be adjusted
- Green propellants can offer $\Delta v$ or spacecraft mass advantages compared to conventional propellants, even for lower $I_{sp}$ and/or density
- Tool will be optimized and extended based on available literature data
Thank you for your attention!
References/Sources

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- [6] https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Technology_CubeSats
References/Sources

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