Exergy Analysis of Rocket Systems

Andrew Gilbert, Industrial and Systems Engineering and Engineering Management

Overview

Exergy is defined as the useful work available from a system in a specified environment.

First Law Analysis

\[
\Delta m_{\text{propellant}} \left( h_{\text{prop}} + \frac{V^2}{2} \right) - X_{\text{des}}
\]

Second Law Analysis

\[
\Delta KE_{\text{vehicle}} + \Delta PE_{\text{vehicle}}
\]

Exergy analysis allows for comparison between different system designs, and allows for comparison of subsystem efficiencies within system designs. A previously derived exergy equation related to aerospace systems is modified to enable higher fidelity analysis for use with rocket systems.

\[
\Delta m_{\text{propellant}} \left( h_{\text{prop}} + \frac{V^2}{2} \right) - X_{\text{des}} = \Delta KE_{\text{vehicle}} + \Delta PE_{\text{vehicle}}
\]

Exergy analysis is a combination of the first and second laws of thermodynamics, which allows for an overall system efficiency measure to be calculated.

\[
\eta_{\text{exergy}} = 1 - \frac{X_{\text{des}}}{X_{\text{expended}}} = 1 - \frac{\sum_{i=1}^{n_{\text{stage}}} \Delta m_{\text{prop}} \left( h_{\text{prop}} + \frac{V^2}{2} \right)}{X_{\text{des}}}
\]

Key Findings

<table>
<thead>
<tr>
<th>Rocket System</th>
<th>Efficiency</th>
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</thead>
<tbody>
<tr>
<td>Saturn V (Apollo 11)</td>
<td>21.56%</td>
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<tr>
<td>Saturn V (Apollo 17)</td>
<td>21.40%</td>
</tr>
<tr>
<td>Falcon 9 v1.1</td>
<td>11.76%</td>
</tr>
<tr>
<td>Proton M</td>
<td>5.63%</td>
</tr>
</tbody>
</table>

Exergy efficiency analysis is performed on three different rocket systems: two mission profiles of the Saturn V, the SpaceX Falcon 9, and the Russian Proton M. As shown in the table, exergy analysis allows rocket systems to be rank ordered based on a single value of overall system efficiency.

Exergy efficiency analysis has also been performed for the NASA Space Launch System (SLS) baseline vehicle and for multiple SLS Requirements Analysis Cycle (RAC) vehicle configurations.

Explanation

Exergy assessments will enable informed, value-based decision making when comparing alternative rocket system designs, and will allow the most elegant and efficient configuration among candidate configurations to be determined. Exergy efficiency analysis can also be used as an objective function in order to optimize the staging of rocket systems.

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Images from nasa.gov