Study and Development of Throttleable Hybrid Rocket Motors

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For a fixed nozzle throat, throttleability is achieved by controlling the oxidizer flow ⇒ Flow control valve (FCV)

**Advantages**
- Increase trajectory efficiency
- Peculiar mission profiles requiring deep throttling
- Requires to control a single feeding line

**Disadvantages**
- Increase system complexity
- \( o/f \) shifting

**Applications**
- Launchers
- ADV
- Flying test beds
\( \frac{o/f}{f} = \frac{m_{ox}^{1-n} D_{port}^{2n-1}}{4^n \pi^{1-n} a \rho_f L} \)

- Circular port
- Port fuel consumption
- Marxman power law

\( n = 0.5 \Rightarrow \text{no } D_{port} \text{ sensitivity} \)
\( n = 1 \Rightarrow \text{no } m_{ox} \text{ sensitivity} \)
\( n \in [0.45, 0.8] \)

Arbitrary throttling \( \Rightarrow \) o/f shift \( \Rightarrow \) Performance reduction

<table>
<thead>
<tr>
<th></th>
<th>90% HTP</th>
<th>( N_2O )</th>
<th>LOX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum c* [m/s]</td>
<td>1598</td>
<td>1559</td>
<td>1773</td>
</tr>
<tr>
<td>c* Sensitivity [m/s]</td>
<td>-22.4</td>
<td>-16.3</td>
<td>-369.9</td>
</tr>
<tr>
<td>c* Penalty TR=5 (balanced)</td>
<td>95.3%</td>
<td>95.9%</td>
<td>96.2%</td>
</tr>
<tr>
<td>c* Penalty TR=5 (fuel rich)</td>
<td>88.0%</td>
<td>84.5%</td>
<td>82.7%</td>
</tr>
<tr>
<td>c* Penalty TR=10 (balanced)</td>
<td>91.6%</td>
<td>92.8%</td>
<td>93.2%</td>
</tr>
<tr>
<td>c* Penalty TR=10 (fuel rich)</td>
<td>78.3%</td>
<td>78.5%</td>
<td>75.4%</td>
</tr>
</tbody>
</table>
FCV selection

Techniques:
- Pure dissipative valve
- Variable area injection
- Parallel feeding lines
- Variable area cavitating venturi

For a CV:
\[ \dot{m}_{ox} = C_d A_{th} \sqrt{2 \rho_{ox} (p^\circ - p_{sat})} \]

Peculiarities
- variable area \( \Rightarrow \) flow control
- if \( p_{up}^\circ > [0.8 \, 0.9] \) \( p_{down}^\circ \Rightarrow \) tank - combustion chamber uncoupling
This year:

- Flow control valve design concluded
- Integration and testing
- Flow control valve characterization
- Static hybrid rocket motor fire tests
### FCV: Design

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Minimum mass flow range</td>
<td>30 [g/s]</td>
</tr>
<tr>
<td>Maximum mass flow range</td>
<td>300 [g/s]</td>
</tr>
<tr>
<td>Maximum operating pressure</td>
<td>80 [bar]</td>
</tr>
<tr>
<td>Venturi throat diameter</td>
<td>2.2 [mm]</td>
</tr>
<tr>
<td>Upstream throat radius</td>
<td>3.3 [mm]</td>
</tr>
<tr>
<td>Venturi divergence angle</td>
<td>10 [deg]</td>
</tr>
<tr>
<td>Pintle apex angle</td>
<td>10 [deg]</td>
</tr>
<tr>
<td>Maximum pintle stroke</td>
<td>11 [mm]</td>
</tr>
<tr>
<td>Useful pintle stroke</td>
<td>7 [mm]</td>
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### Features

- Conical pintle/spike
- Manually moved pintle
- Pressure tap for feedback

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FCV characterization: Set-up

Features

- HTP tank (piston separator)
- Flow control valve
- Catalytic bed (not shown)
- Test motor (not shown)
- Purging line
FCV characterization: Results

$H_2O$

91 % HTP

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FCV characterization: Results

\[ H_2O \]

\[ C_{D,H_2O} = 1.008 - 2.626 \times - 93.14 \times x^2 - 4.643 \cdot 10^{-5}/x, \quad R^2 = 0.93 \]

\[ C_{D,HTP} = 1.003 - 0.7345 \times - 174.5 \times x^2 - 3.086 \cdot 10^{-5}/x, \quad R^2 = 0.86 \]
A test campaign was conducted to characterize the test motor behavior with different mass flows. Tests were conducted in the fuel rich region.

\begin{center}
\begin{tabular}{c|c|c|c}
Test # & $\dot{m}_{HTP}$ [g/s] & $t_b$ [s] & $p_{cc}$ [bar] \\
\hline
1 & 56.5 & 25 & 8.6 \\
2 & 137.9 & 16 & 20.9 \\
3 & 219.0 & 7 & 33.1 \\
4 & 282.1 & 5 & 43.5 \\
\end{tabular}
\end{center}
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Conclusion and Future work

- A variable area cavitating venturi to be used as flow control valve in hybrid rocket motors was developed and characterized.
- Our test motor was tested with four different oxidizer mass flows reaching a 1:5 throttling ratio.
- Automatically control the pintle stroke implementing a DC motor.
- Characterize the dynamic behavior of flow control valve and test motor.
- Throttling tests.
Thank you! Any question?