Development and Testing of a Small Hybrid Rocket Motor for Space Applications

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Introduction to HRMs

Liquid rocket motors

Solid rocket motors

Hybrid rocket motors
Introduction to HRMs

Hybrid motors advantages:

- Safety
- Simplicity
- Reliability
- Low cost
- Start, stop, restart
- Thrust control
- Environmental friendliness

Hybrid motors issues:

- Low regression rate
- Low combustion efficiency
- Fuel residuals
- Low volumetric loading
- Mixture ratio shift
Possible solutions to main issues:

- Solid fuel additives
- Liquefying solid fuels
- Diaphragms
- Nonconventional injector designs
Introduction to HRMs

Entrainment

Thermomechanical properties

\[ \dot{f} = 0.488 \overline{G_{\text{ox}}}^{0.62} \]

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Introduction to HRMs

Axial injection

Swirl injection
Applications of small HRMs

- Sounding rockets
- Deorbiting systems
- Orbit raising and reentry maneuvering systems
- Maneuverable adapter rings
Hybrid rocket propulsion group heritage
Hybrid rocket propulsion group heritage
Suitable hybrid rocket envelope:

\[ R = \frac{D_f}{D_0} \quad \frac{G_0}{G_f} = R^2 \]

\[ VL = 1 - \frac{1}{R^2} \]

\[ \frac{\alpha G_0^n t_b}{D_0} = \frac{R^{2n+1} - 1}{(4n + 2)} \]

Graphs showing volume loading, diameter \( D_0 \) as a function of \( R \) and burning time, and diameter \( D_0 \) with lines for high and low \( r \).
Relation between motor size and burning time:
- Parametric with volume loading
- Parametric with regression rate

High regression rate is needed for large motors and high volume loading
Numerical investigation

Main objectives of the investigation:
- Support the design of the small scale HRM
- Quantify the combustion efficiency varying the injection
- Assess the effect of the post-chamber length
- Determine the wall heat flux to the thermal protections
Several configurations analyzed:

- Different injection intensities
- Different post-chamber lengths
- Different grain internal diameters
Results of the numerical simulations:

- All the configurations achieved high efficiency $\eta > 95\%$
- The oxidizer mass fraction is almost zero when the mass flow reaches the end of the post chamber
- A longer post chamber results in higher efficiency
- The wall heat flux increases with the intensity of the injection
Experimental activity
Experimental activity

Hybrid 1 kN motor:
- Catalytic reactor
- Combustion chamber

Catalytic reactor:
- Decomposes the 90% HTP to oxygen and water
- Gaseous form with a temperature of about 700-800 °C

Combustion chamber:
- Steel cylinder and two flanges (MEOP=40 bar and SF=4)
- Convergent nozzle
- 22 sensor holes (thermocouples and pressure sensors)
- Fuel either HDPE or paraffin
Experimental activity

Fluidic line:
- High-pressure nitrogen tank
- Pressure regulation block
- Hydrogen peroxide tank
- Tubes and automated ball valves
- Variable area cavitating venturi
Swirl oxidizer injection

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<th>$L_{pc}$ [mm]</th>
<th>$D_p$ [mm]</th>
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Swirl oxidizer injection

Results of the numerical simulations:

- All the configurations achieved high efficiency $\eta > 95\%$
- Higher geometric swirl number increase the regression rate of the solid fuel grain
- Shorter post-chambers have a lower influence on the global mixture ratio
Swirl oxidizer injection

Marxman’s regression rate law:

- Regression rate of the solid fuel grain \( \dot{r} = aG^n \)
- Oxidizer mass flux \( G = \frac{m_{ox}}{A_p} \)

- Using the experimental results it is possible to calculate the values of \( a \) and \( n \)
- The value of \( n \) is almost 0.5 meaning that the fuel mass flow rate is approximately constant with the grain port diameter

Relation between \( SN_g \) and the coefficient \( a \):

- An almost linear relation has been found (at least in the range of \( SN_g \) studied)
- The regression rate can be easily varied simply changing the injection plate
Throttleability is achieved by controlling the oxidizer flow

Advantages:
- Trajectory control
- Peculiar mission profiles

Disadvantages:
- Increase system complexity
- $O/F$ shift and $c^*$ penalties
Real time throttling
Real time throttling
The study focuses on two main objectives:

- Demonstrate the feasibility of a HTP/paraffin hybrid motor with a long burning time.
- Demonstrate paraffin liquid layer theory: heat does not penetrate inside the fuel grain during the burn.

A HTP/paraffin lab-scale motor has been designed, built and tested at the hybrid propulsion group facility.
Test results:

- Successful long burn test
- Constant oxidizer mass flow
- No nozzle throat erosion
- Constant pre-cc and post-cc pressures
- Small pressure oscillations
- Regression rate exponent $n=0.5$
- Regression rate exponent $a=0.145$
Long burning time

Temperature sensors:

- In wax 1-2: constant temperature until a steep increase around second 55 (thermocouples 10 mm inside the grain)
- Out steel 1-2: negligible temperature variation
- Out steel nozzle: continuous increment of the temperature (no insulation around the graphite and molybdenum parts)
Conclusions

A small scale hybrid rocket motor was developed and extensively tested

Analytical model:

- The operating range for single port hybrids was found
- High regressing fuels are better suited for larger thrusts—shorter burning times, while the opposite occurs for low regressing fuels

Numerical investigation:

- Support the design process
- All the configurations achieved high efficiency
- A longer post chamber gives just slightly higher efficiency
- A too high injection swirl intensity causes unacceptable heat fluxes to the thermal protections
Conclusions

Experimental activity:
- Swirl oxidizer injection
- Real time throttling
- Long burning time

Swirl oxidizer injection:
- All the configurations achieved high efficiency, thus shorter post chambers are preferable because they have a lower influence on the global mixture ratio
- An almost linear relation between $SN_g$ and $\alpha$ has been found, thus the regression rate can be easily changed during the design phase depending on the mission requirements

Real time throttling:
- Dynamic throttling with a maximum throttling ratio of 12.6:1
Conclusions

Long burning time:

- The motor burned for 80 s in fuel-rich conditions
- The pressure profile was stable and flat showing no sign of grain failure/degradation
- The flat pressure profile without nozzle erosion also suggests a regression rate exponent near 0.5
- Two thermocouples were inserted in the fuel grain that demonstrated the validity of the liquid layer theory
Thank you for your attention!

Any questions?