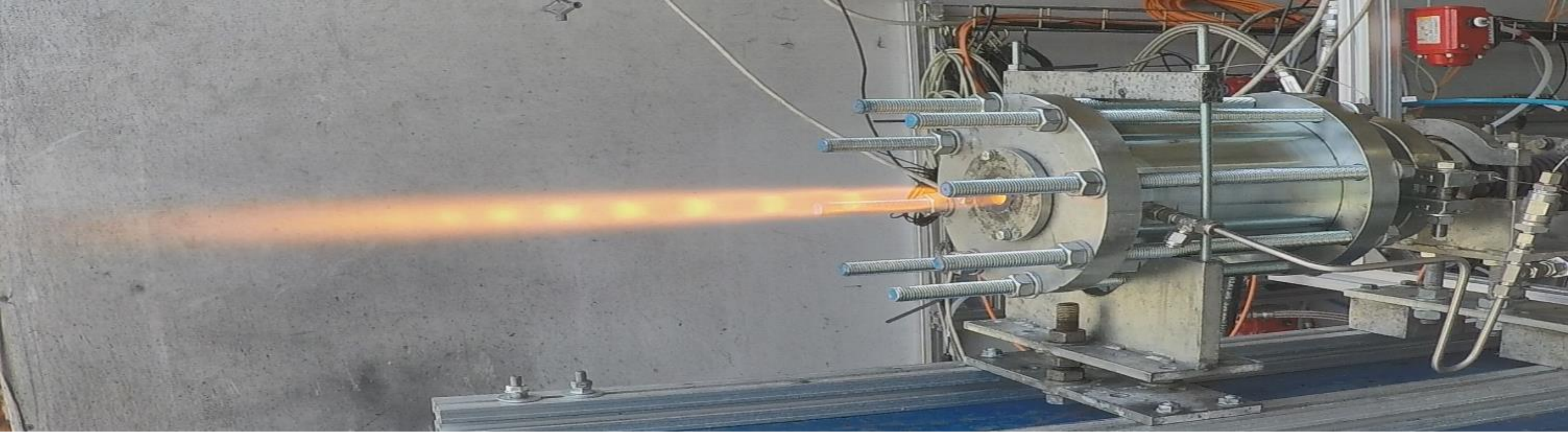


Enrico Paccagnella

13 September 2019

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

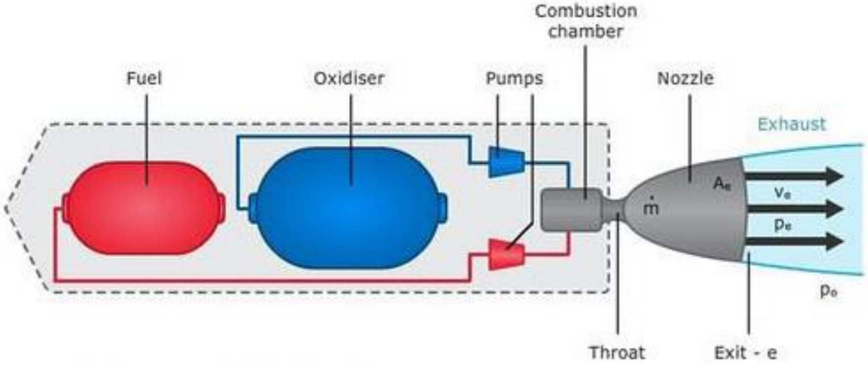
Università degli Studi di Padova

Centro di Ateneo di Studi e Attività Spaziali “Giuseppe Colombo”

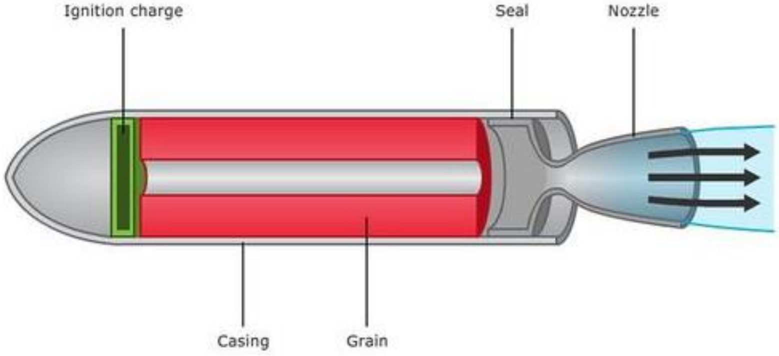
Università degli Studi di Padova

CISAS G. COLOMBO

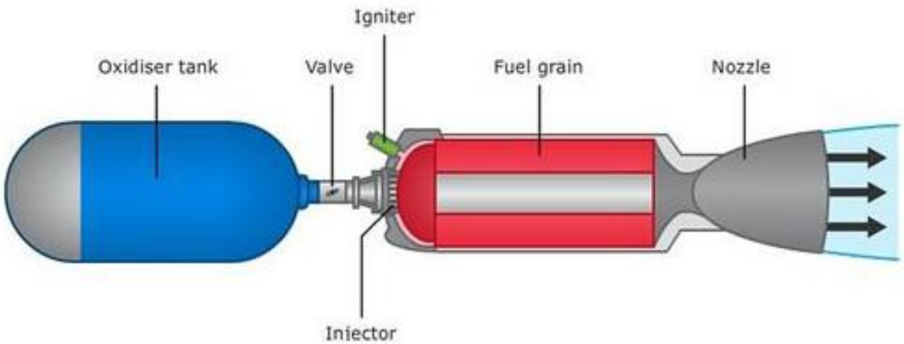
Introduction to HRMs



Liquid rocket motors



Solid rocket motors



Hybrid rocket motors

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

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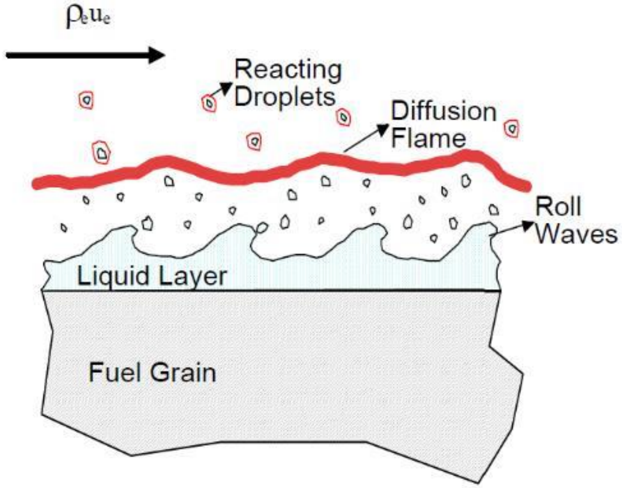
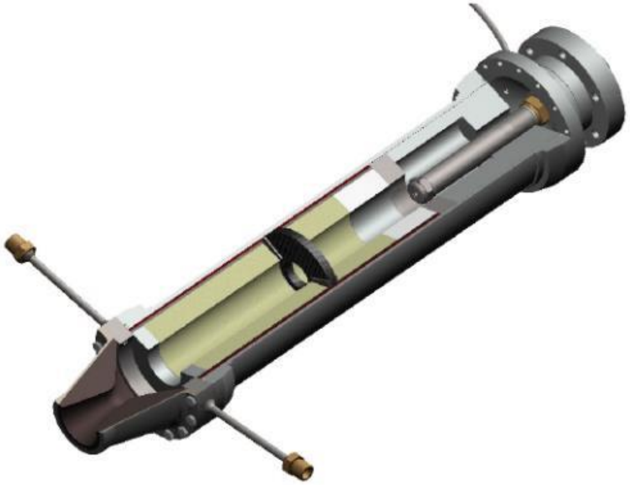
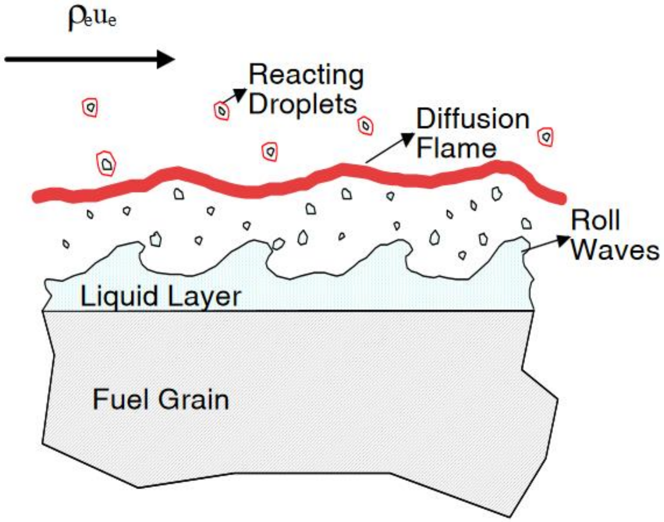
Possible solutions to main issues:

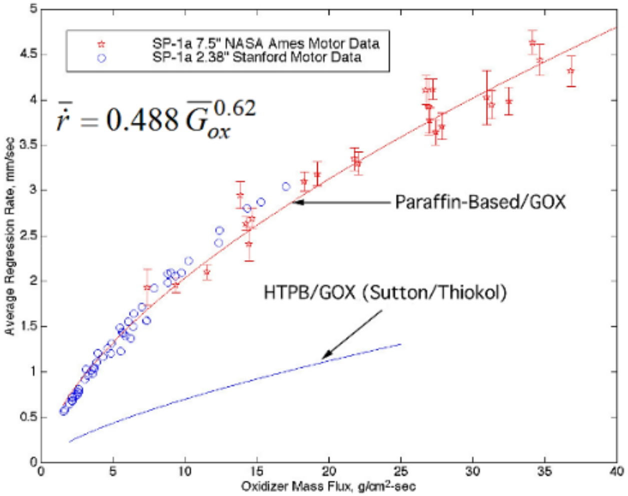
- Solid fuel additives
- Liquefying solid fuels
- Diaphragms
- Nonconventional injector designs



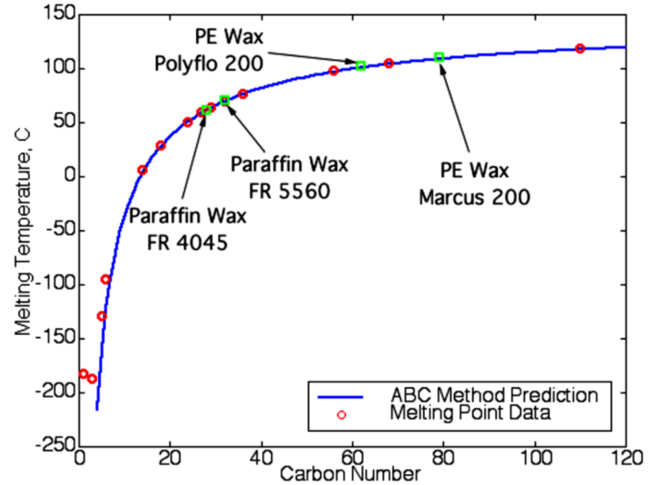


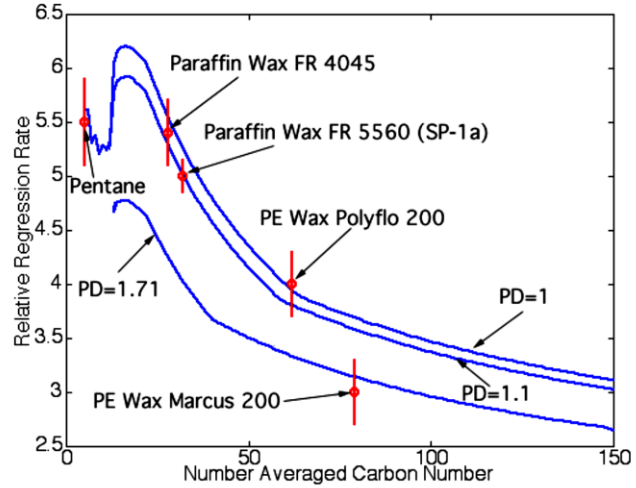
Entrainment





Thermomechanical properties





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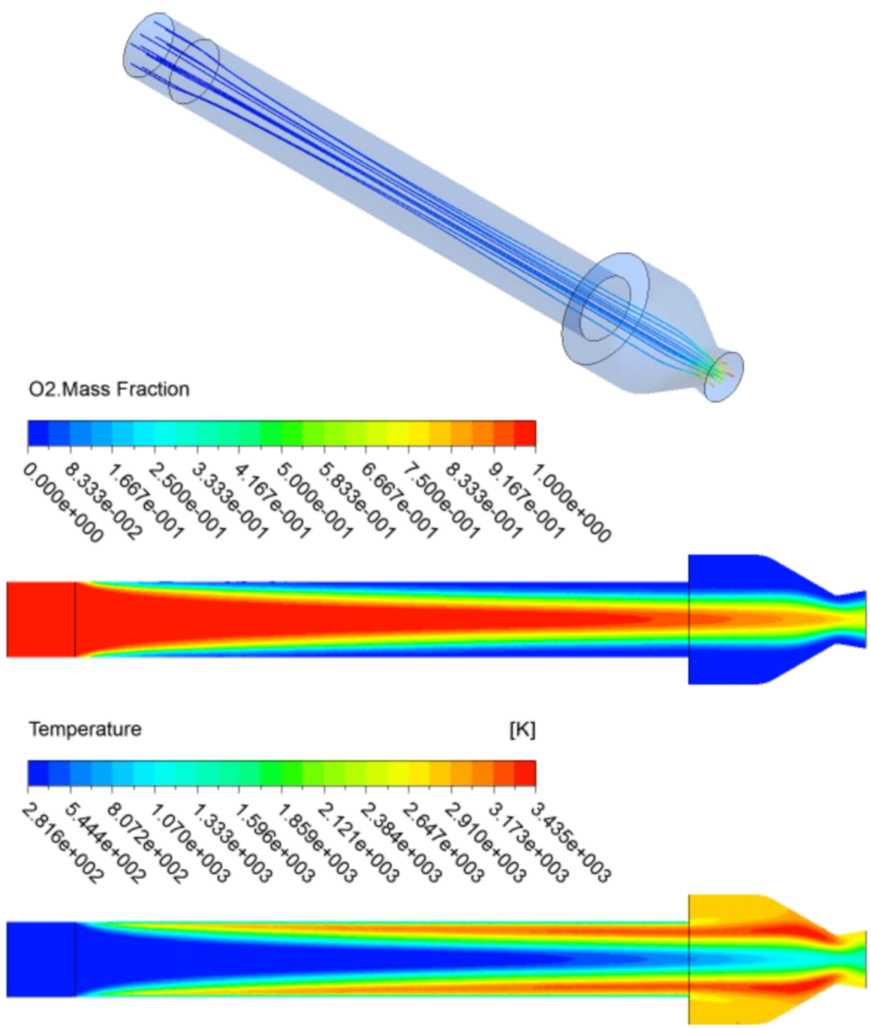
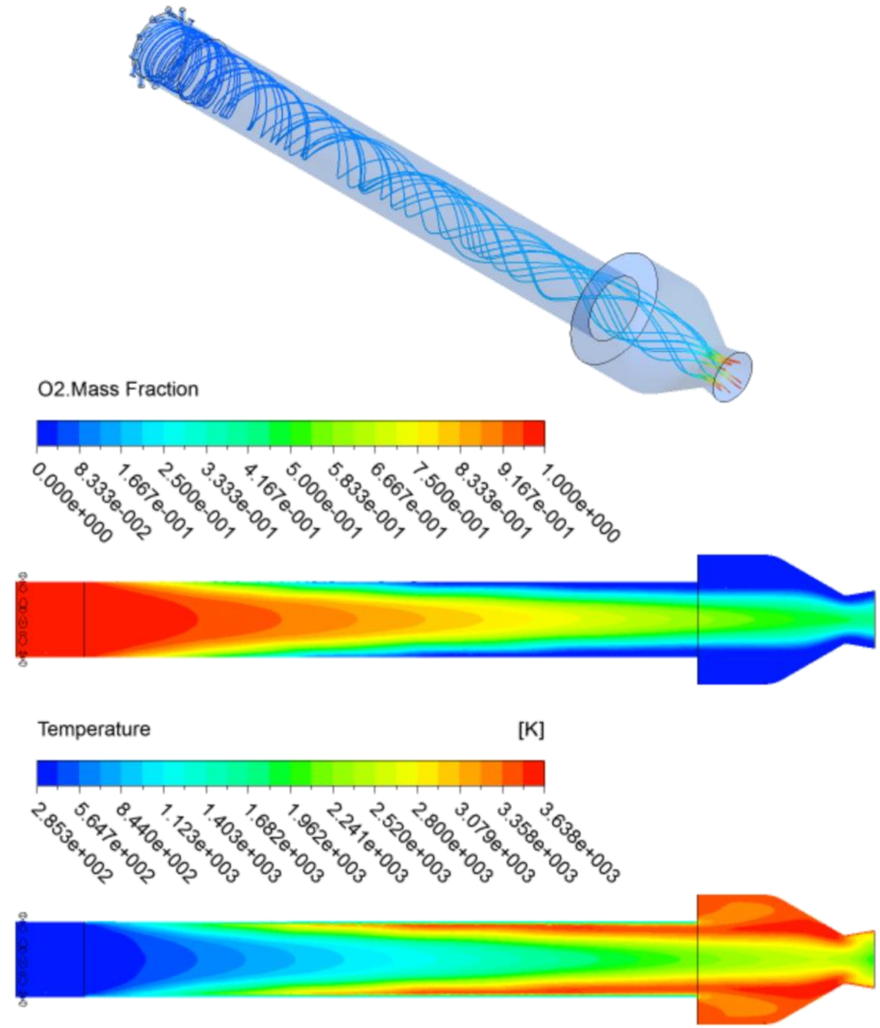
Axial injection



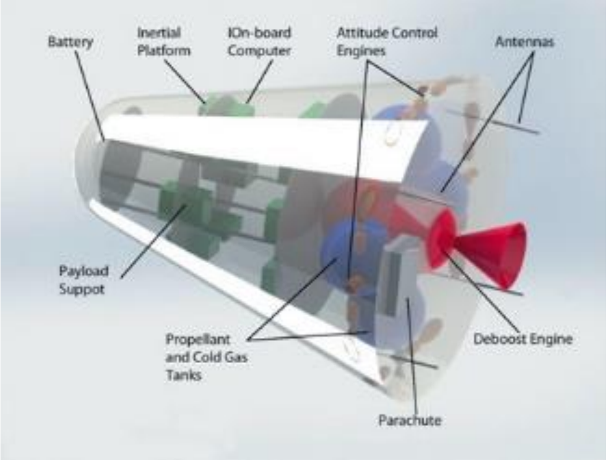
Swirl injection



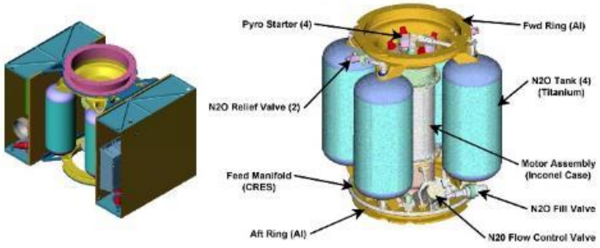
Applications of small HRMs

Sounding rockets

Deorbiting systems

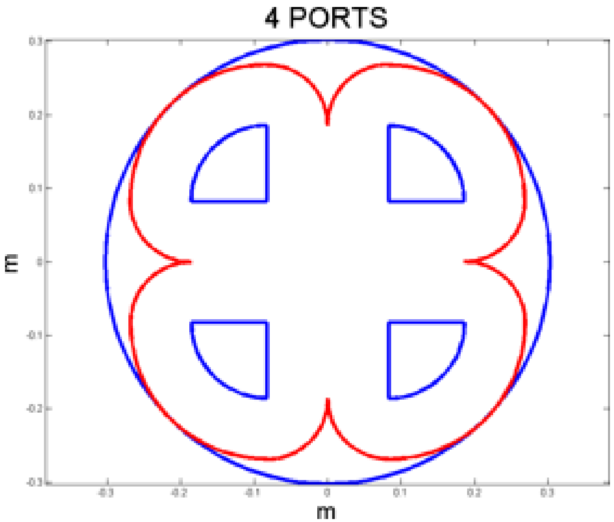


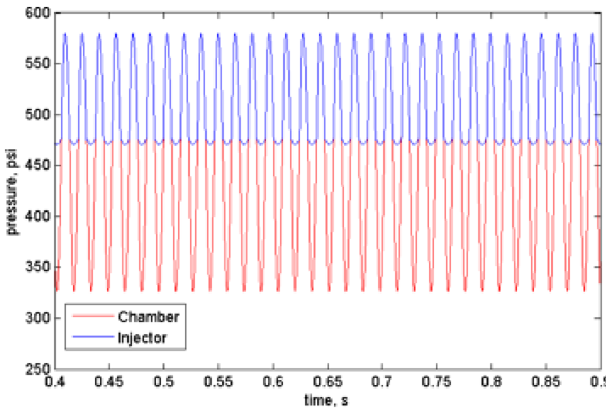
Orbit raising and reentry maneuvering systems

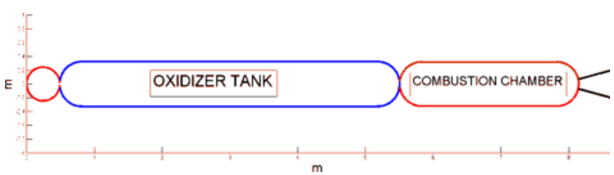


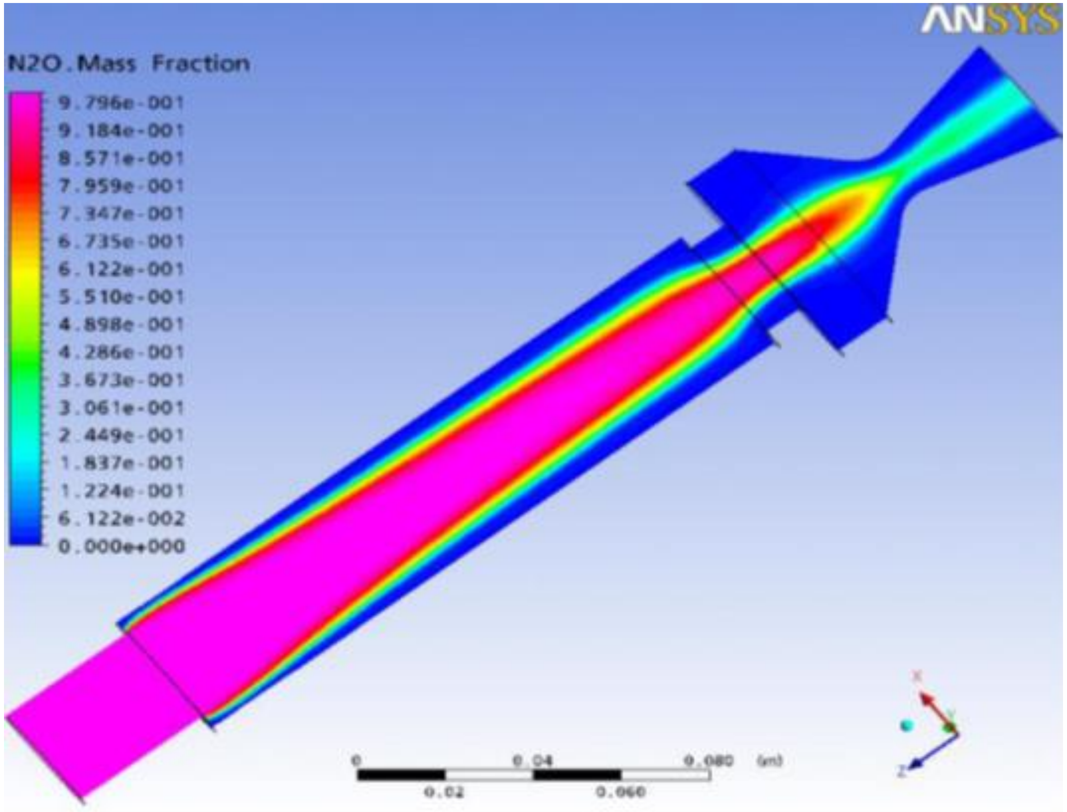
Maneuverable adapter rings

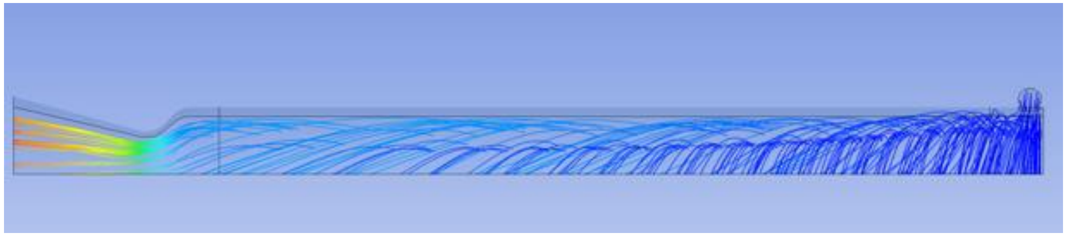
Hybrid rocket propulsion group heritage











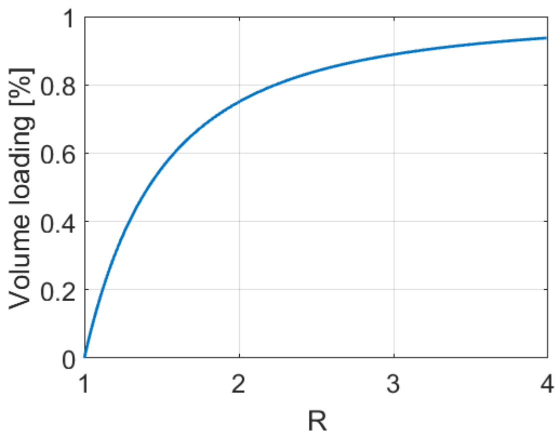
Hybrid rocket propulsion group heritage

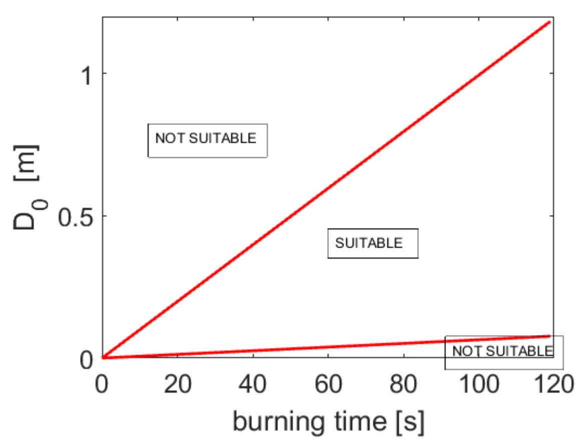
Suitable hybrid rocket envelope:

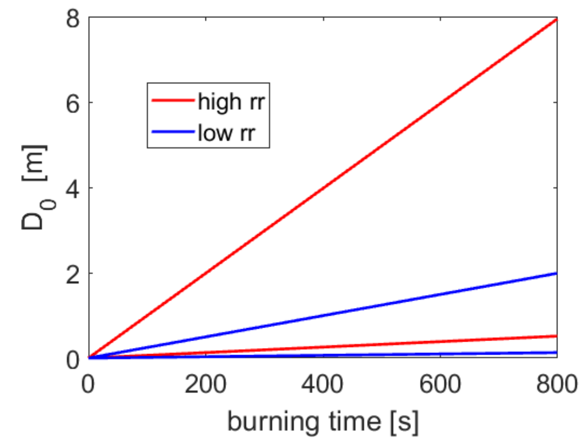
$$R = \frac{D_f}{D_0} \qquad \frac{G_0}{G_f} = R^2$$

$$VL = 1 - \frac{1}{R^2}$$

$$\frac{a G_0^n t_b}{D_0} = \frac{R^{2n+1} - 1}{(4n + 2)}$$

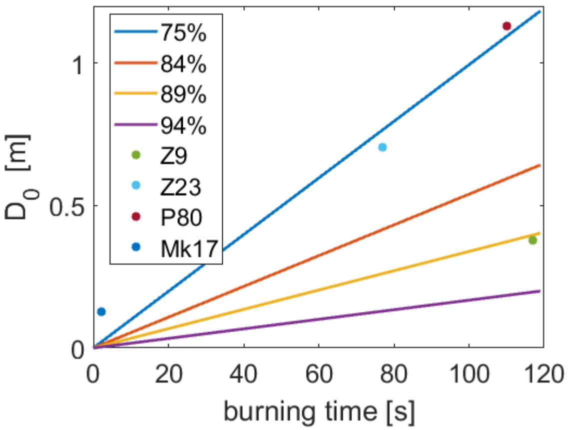


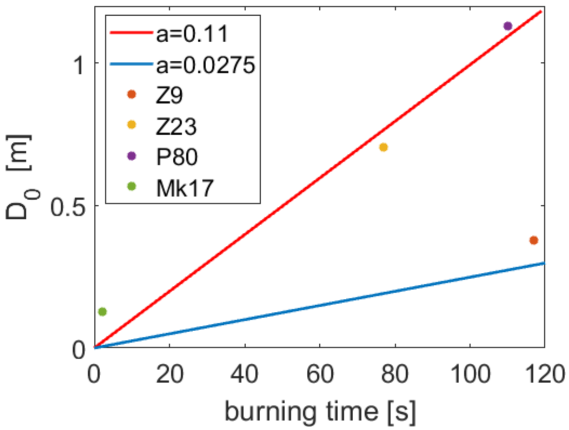




Relation between motor size and burning time:

- Parametric with volume loading
- Parametric with regression rate

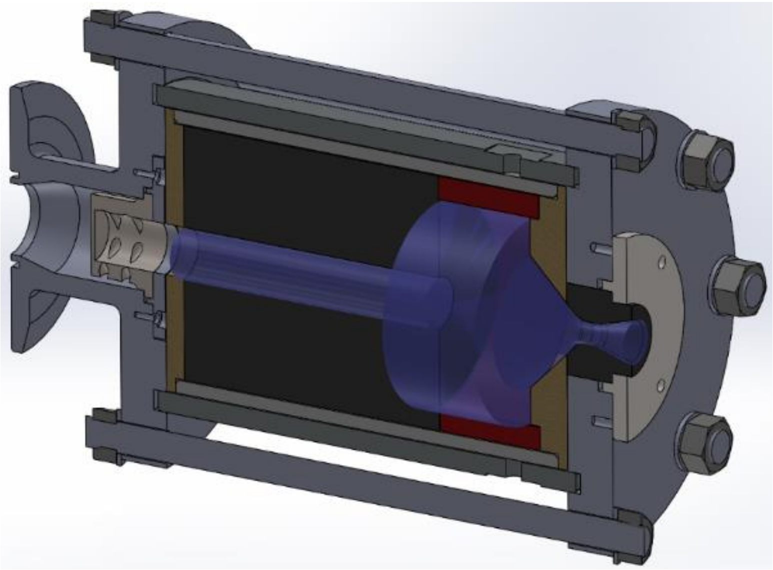


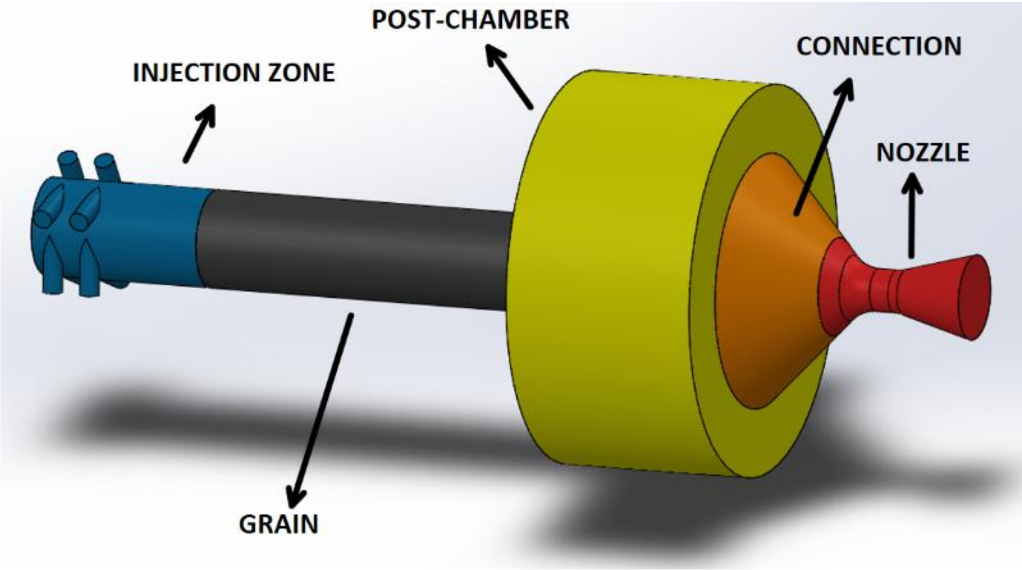


High regression rate is needed for large motors and high volume loading

Main objectives of the investigation:

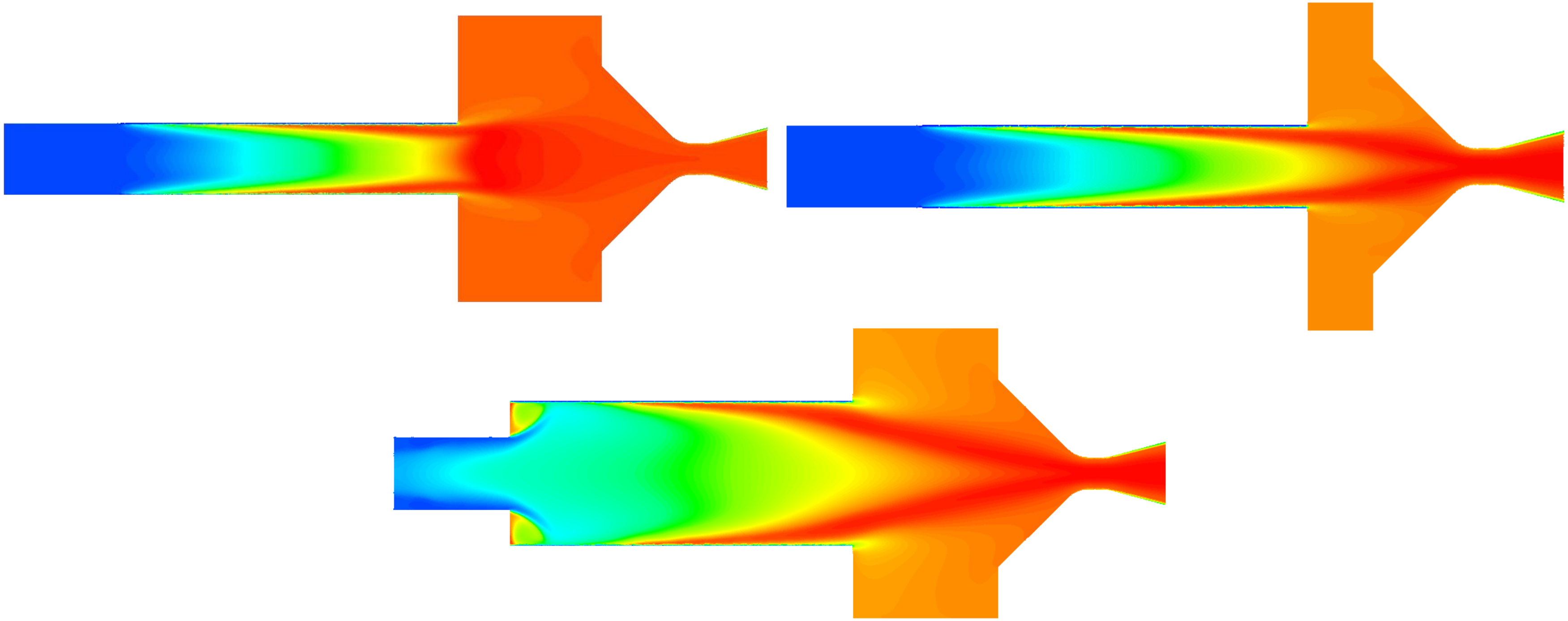
- Support the design of the small scale HRM
- Quantify the combustion efficiency varying the injection
- Assess the effect of the post-chamber length
- Determine the wall heat flux to the thermal protections





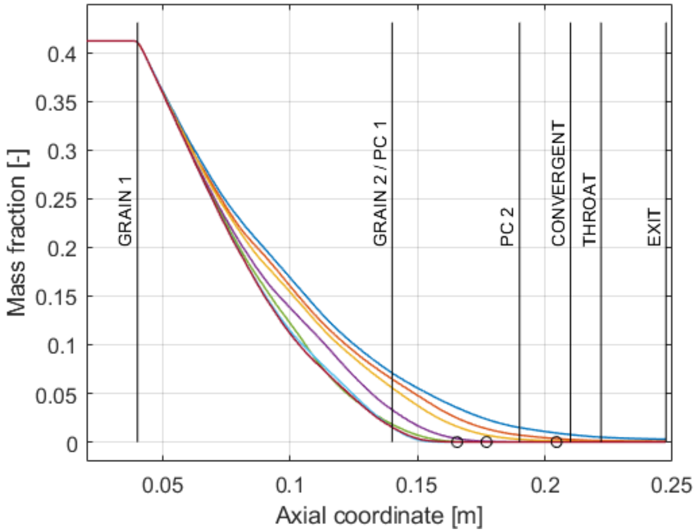
Several configurations analyzed:

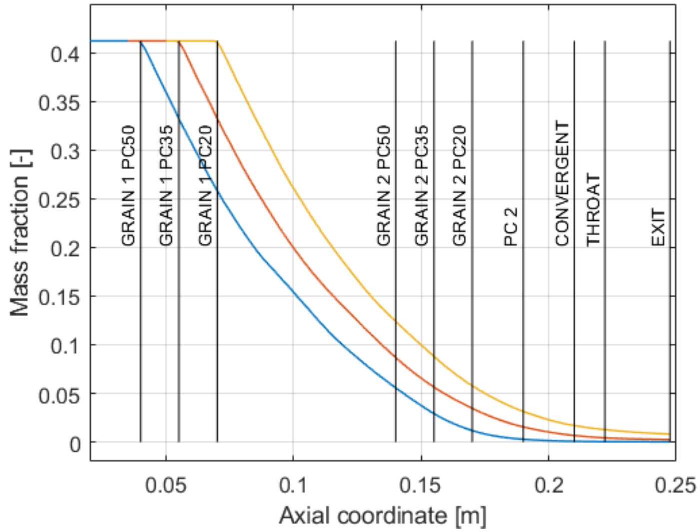
- Different injection intensities
- Different post-chamber lengths
- Different grain internal diameters



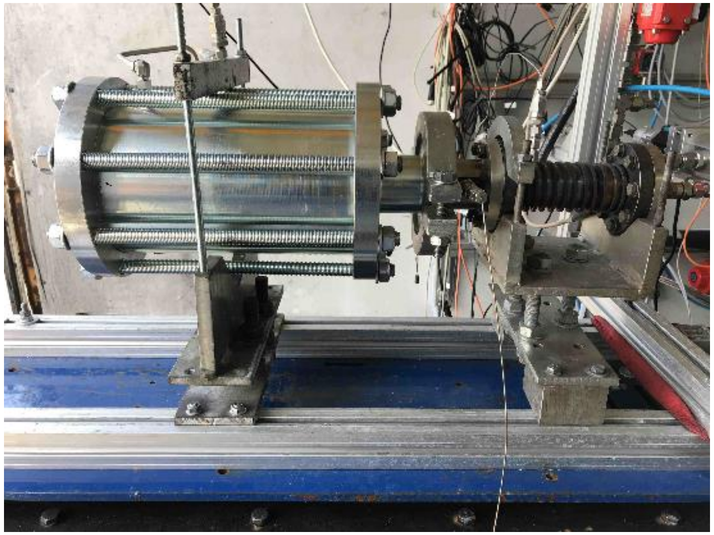
Results of the numerical simulations:

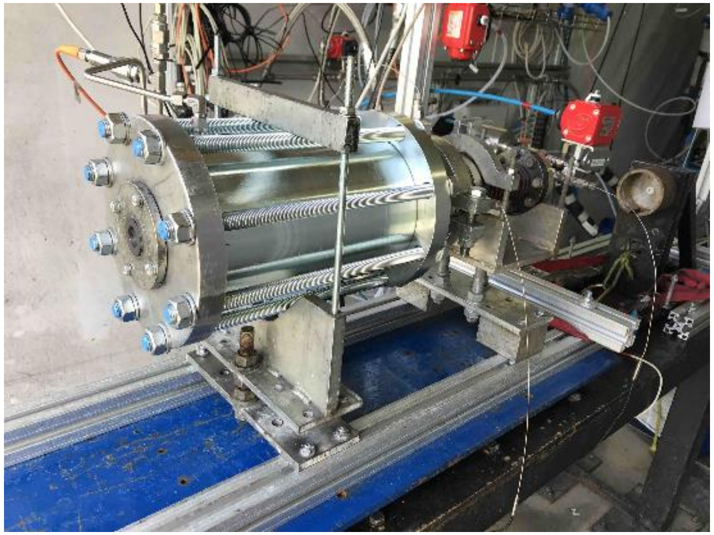
- All the configurations achieved high efficiency η > 95 %
- The oxidizer mass fraction is almost zero when the mass flow reaches the end of the post chamber
- A longer post chamber results in higher efficiency
- The wall heat flux increases with the intensity of the injection

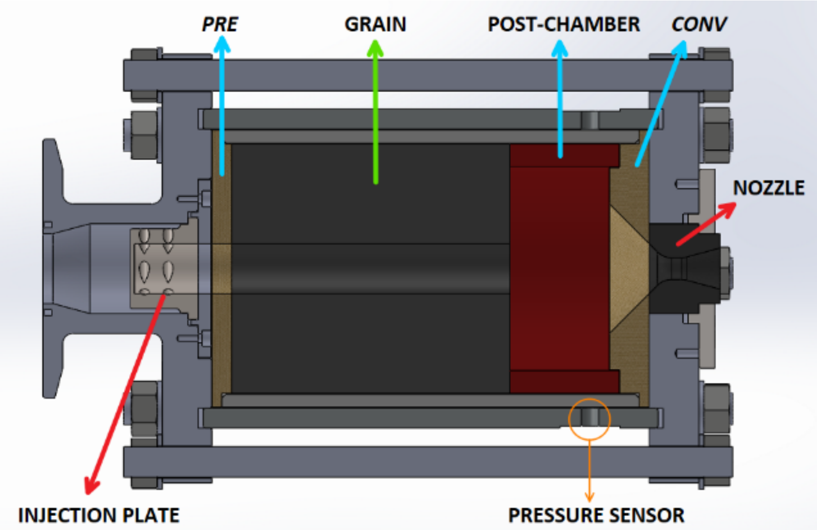




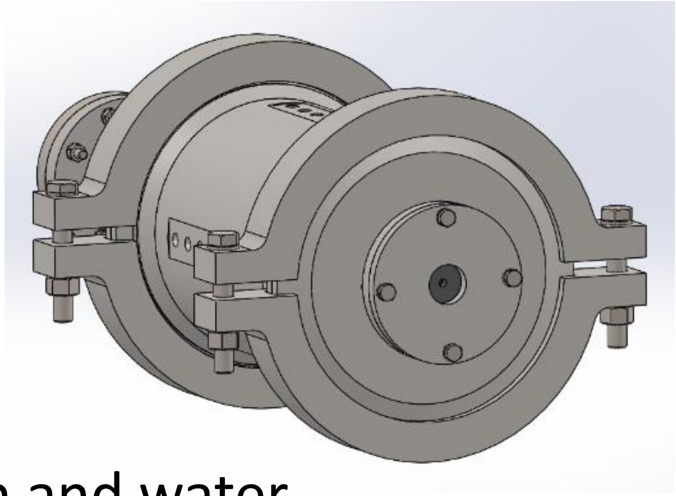
Experimental activity







Experimental activity



Hybrid 1 kN motor:

- Catalytic reactor
- Combustion chamber

Catalytic reactor:

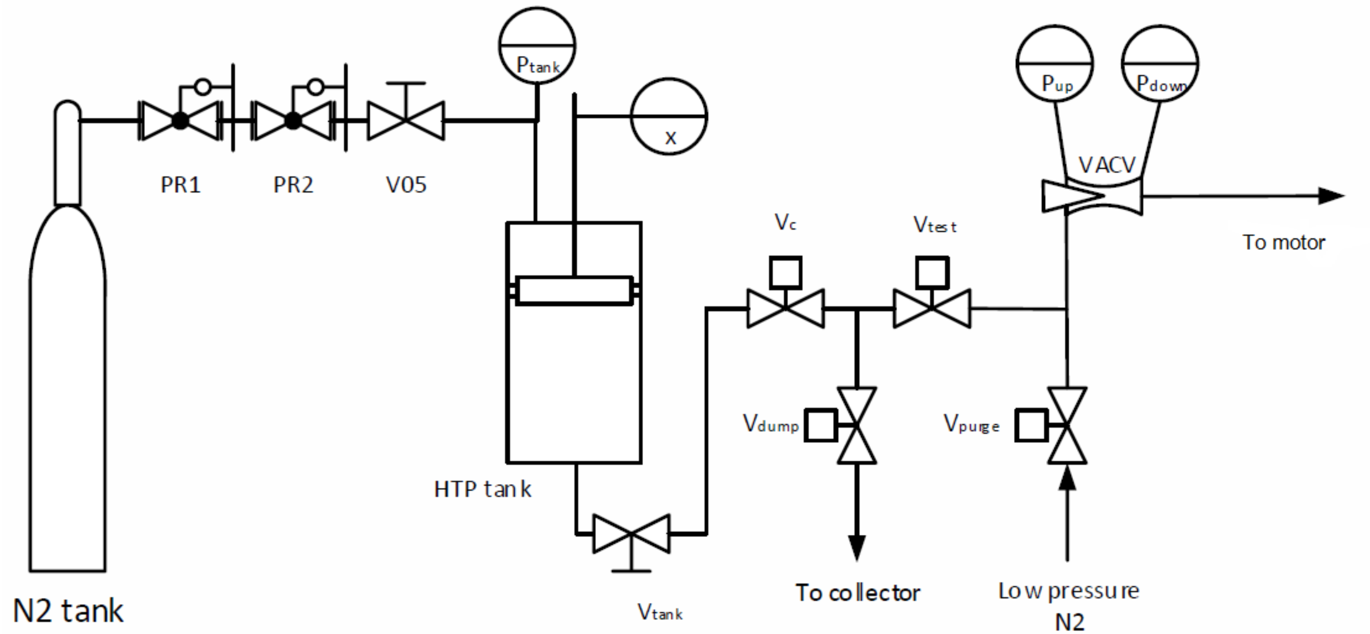
- Decomposes the 90% HTP to oxygen and water
- Gaseous form with a temperature of about 700-800 °C

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

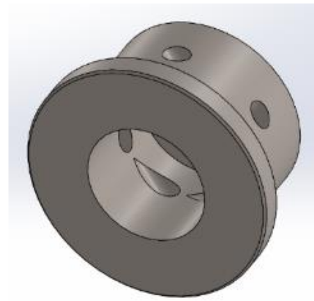
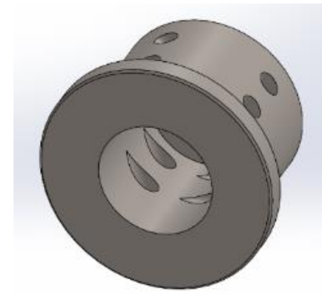
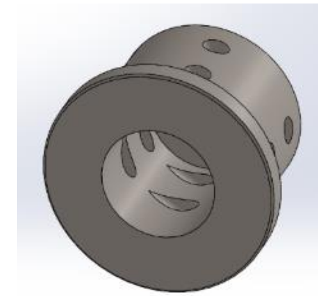
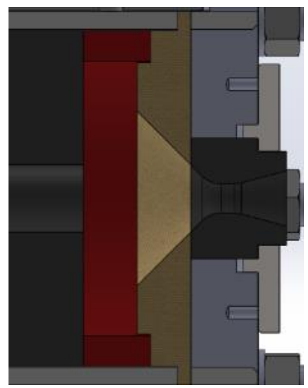
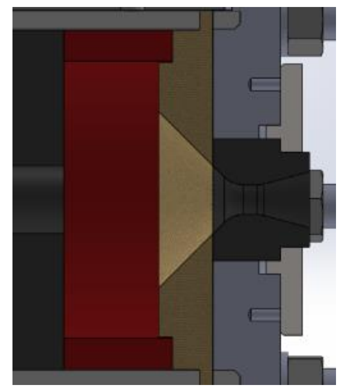
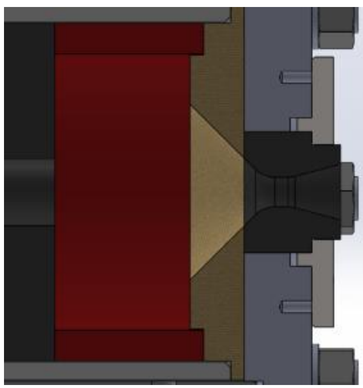
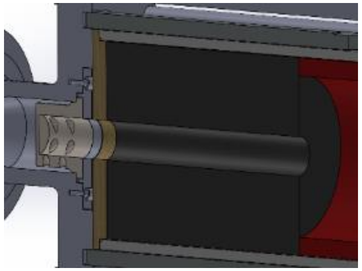
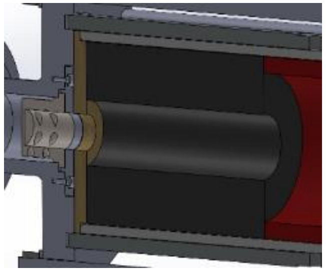
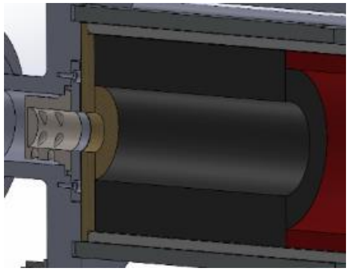
Fluidic line:

- High-pressure nitrogen tank
- Pressure regulation block
- Hydrogen peroxide tank
- Tubes and automated ball valves
- Variable area cavitating venturi



Swirl oxidizer injection

#	SN_g [-]	L_{pc} [mm]	D_p [mm]
1	2	20	25
2	2	50	25
3	2	50	43.5
4	2	50	56
5	2.53	20	25
6	2.53	35	25
7	2.53	50	25
8	2.53	50	46.5
9	2.53	50	61
10	3.33	20	25
11	3.33	35	25
12	3.33	50	25
13	3.33	50	50
14	3.33	50	66.5

Swirl oxidizer injection

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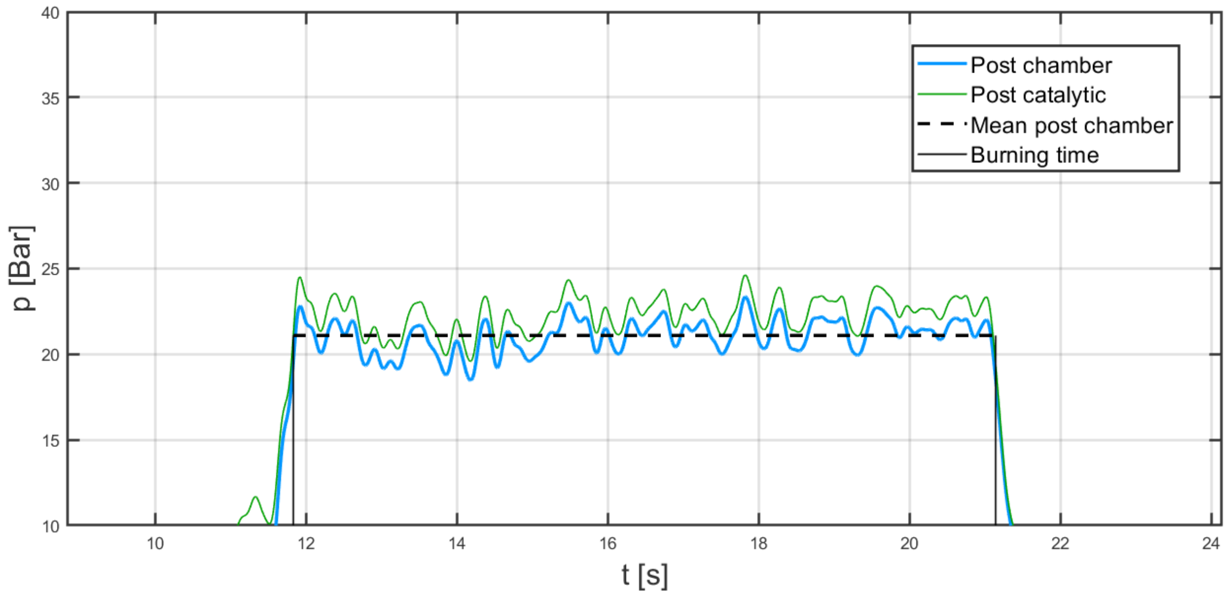
Results of the numerical simulations:

- All the configurations achieved high efficiency η > 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



Marxman's regression rate law:

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

Real time throttling

Throttleability is achieved by controlling the oxidizer flow

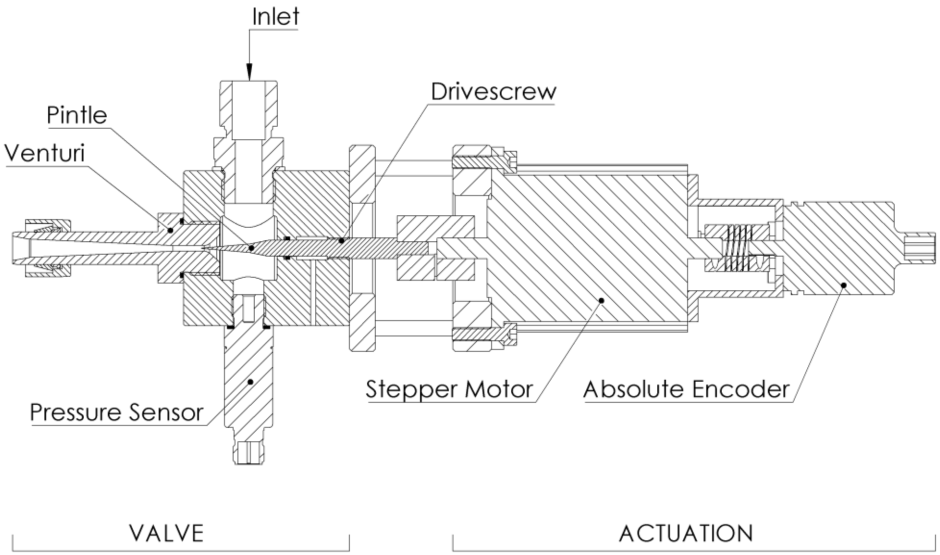
Advantages:

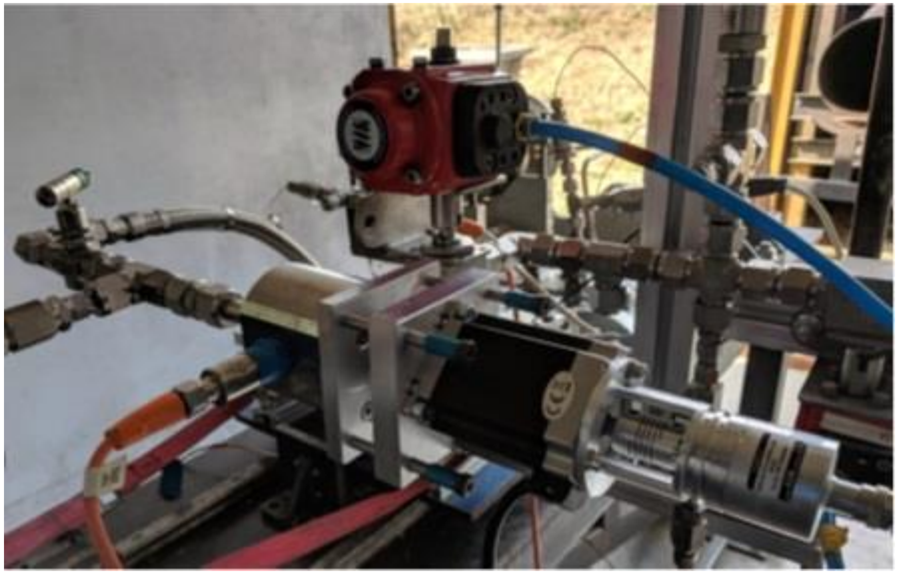
- Trajectory control
- Peculiar mission profiles

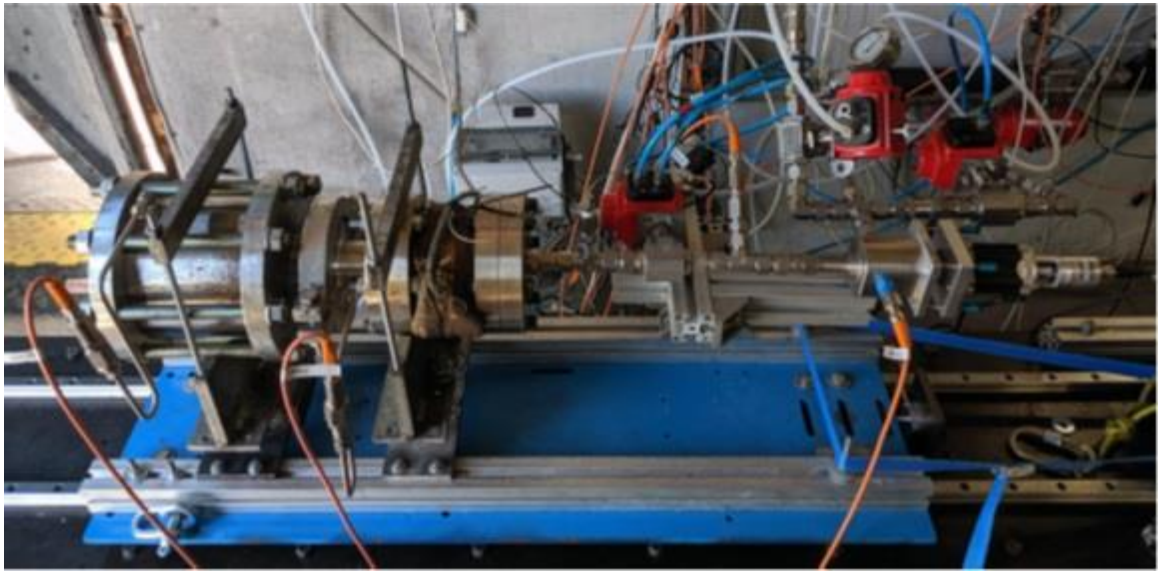
Disadvantages:

- Increase system complexity
- *O/F* shift and c^* penalties

Real time throttling







Real time throttling

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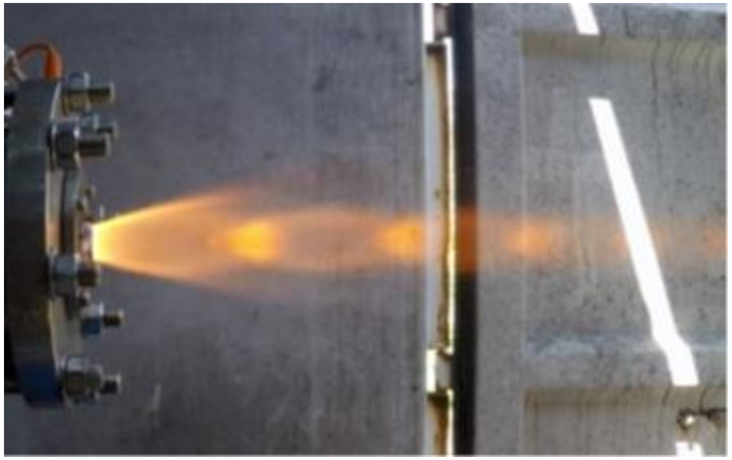
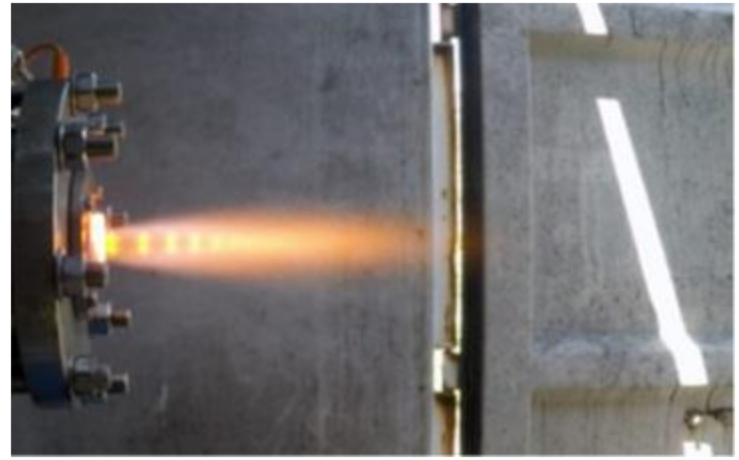
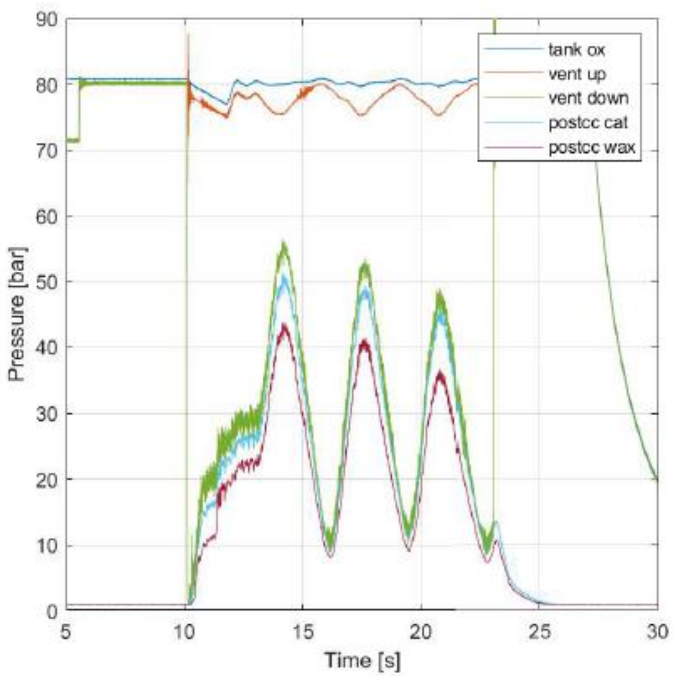
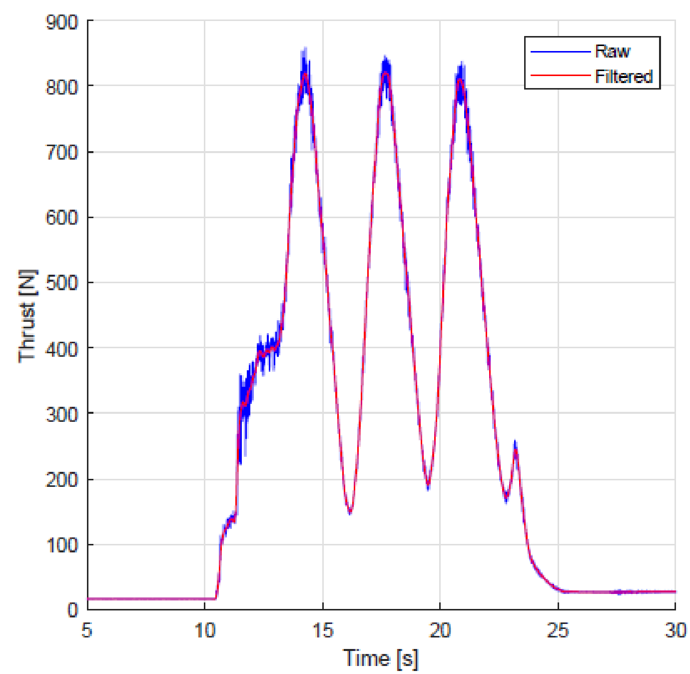


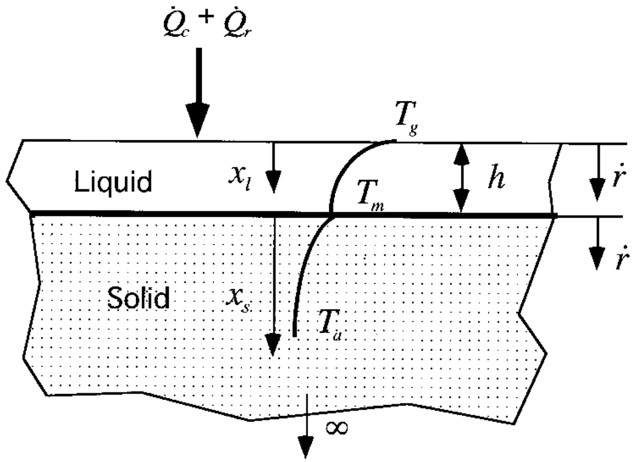


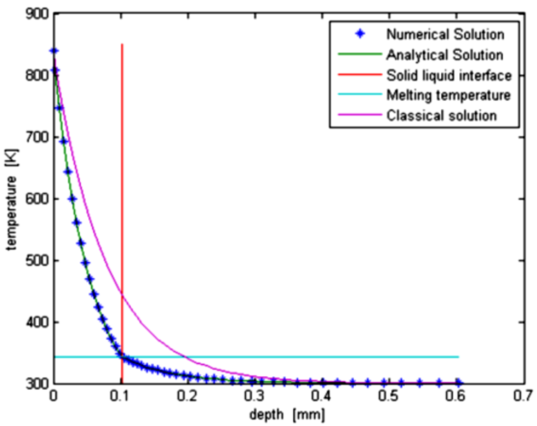




The study focus on two main objectives:

- 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

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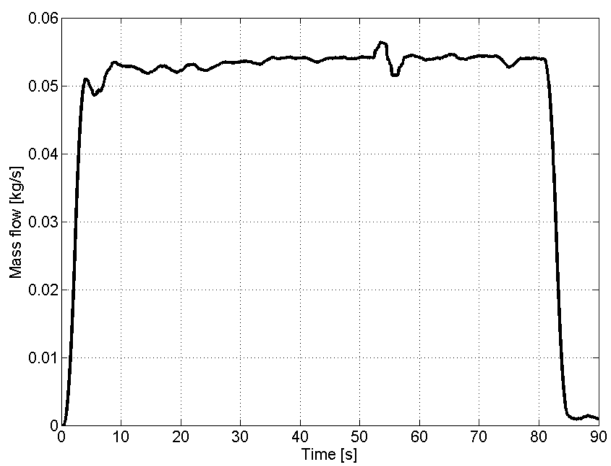
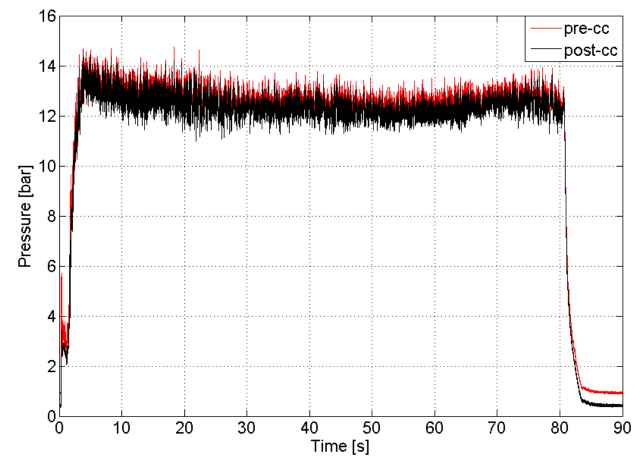
Test results:

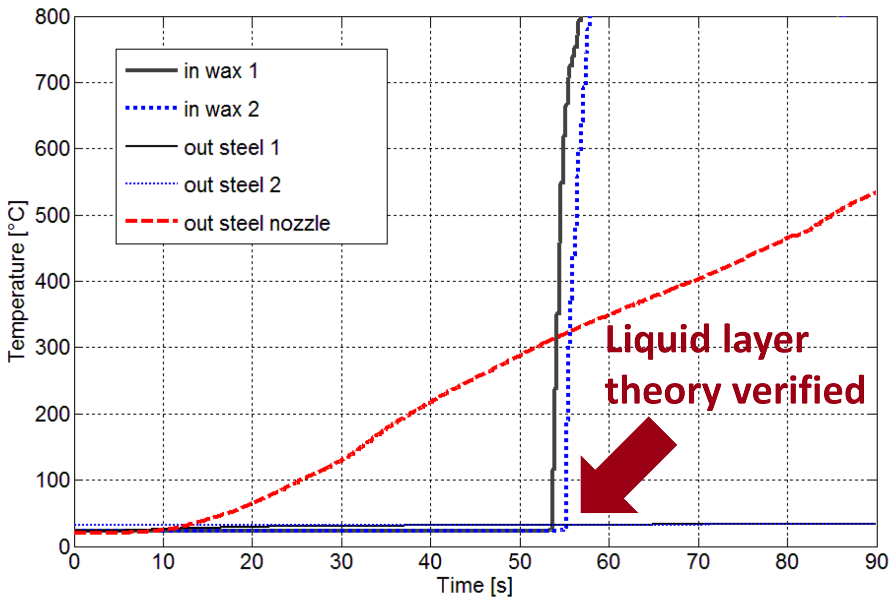
- Successful long burn test
- Constant oxidizer mass flow
- No nozzle throat erosion
- Constant pre-cc and post-cc pressures
- Small pressure oscillations
- Regression rate exponent n=0.5
- Regression rate exponent a=0.145

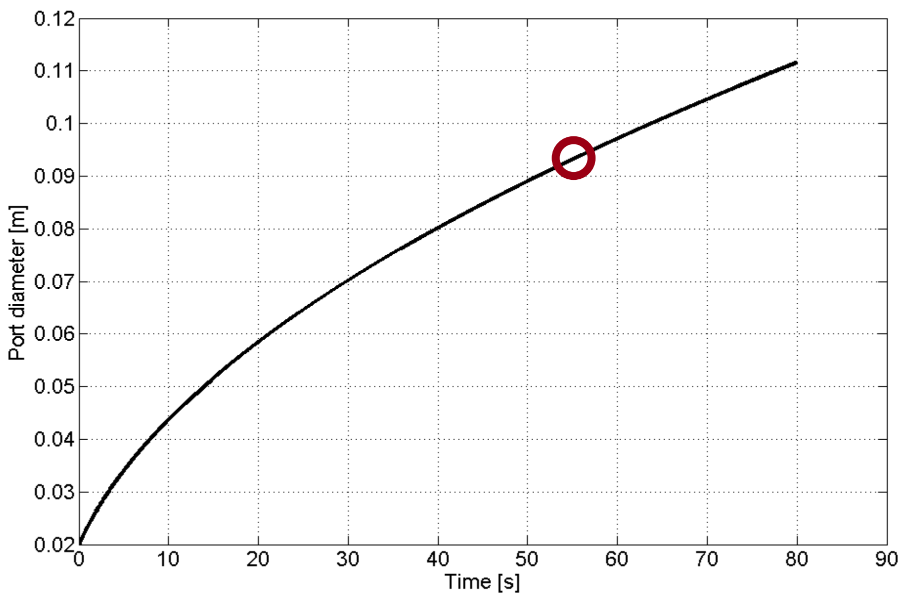




Temperature sensors:

- 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 a 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?