

Numerical and Experimental Study of a 230 N Paraffin/N₂O hybrid rocket

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Abstract

The goal of this paper is to define a methodology for the preliminary design of a hybrid rocket test bench with the support of theoretical and numerical investigation. A preliminary analysis of the possible failures, overpressures and back flows is mandatory to setup a safe test bench. 3DRANS for different port diameter have been simulated to account for the port diameter increase in time. Depending on that, simulations predicted overpressures in the pre-combustion chamber, also confirmed by experimental tests. With the support of numerical results, initial and operative conditions have been modified in order to work in safe conditions.

1. Introduction

Nowadays, the aerospace market is growing mainly at the expense of a huge demand for launching services, like the orbit placement of networking and communication satellites, but also in Space tourism and the decommissioning of space shuttle. Therefore, there is great need and demand for chemical propulsion which allow low costs, simple and eco-friendly, without compromising with good level of performance. It is in the context that many scientists and researchers are showing their high interest in the hybrid rocket engine [1].

In fact, hybrid rocket propulsion may be considered the challenge for new generation of space launchers since they demonstrated promising performance when compared with LRE, i.e., simplicity lower cost, reliability and higher specific thrust; and also when compared with SRE, i.e., safety (low explosion risk), eco-friendly (less toxic), start - stop - restart and throttling capabilities and higher specific Impulse.

However, the main disadvantage is very low burning rate and a not constant O/F ratio in time.

Hybrid rocket engine is the subject of research from last many decades, using different compounds for fuel and oxidizer. The first attempts at hybrid rocket engine were made by soviet researches in the early 1933 who used a coagulated form of gasoline along with liquefied oxygen. Later, in 1937, attempts in Germany used fuel/oxidizer combination of coal with N₂O or graphite with liquid oxygen [4], [5]. In 1953, the Pacific Rocket Society used wood from Douglas fir trees as the fuel for a series of hybrid rockets [5]. Later tests by General Electric used hydrogen peroxide and polyethylene [6]. After these initial attempts, the fuel of choice was typically gradually settled on the HTPB+N₂O combination that was eventually used in what is perhaps the best-known application of a hybrid rocket motor, SpaceShipOne, produced by Mojave Scaled Composites [7], which won the Ansari X-prize in 2004. SpaceShipOne was further developed into SpaceShipTwo, a suborbital spaceplane designed for space tourism, and owned by Virgin Galactic [8].

Recently, lab-scale investigations [9] have demonstrated that Paraffin has 3-4 times higher regression rate compared to HTPB. Actually, pure paraffin fuel grains soften when heated; hence, paraffin fuel grains can potentially slump during firing if evaporation times are longer than burning times.

2. Classification of hybrid propellant

In order to define the best performing hybrid propellant, a comparison among the most widely used propellants has been performed. Concerning the oxidizers, liquid oxygen, nitrogen oxide, hydrogen peroxide and Nytrox have been investigated. LOx boasts the higher specific impulse and a low O/F ratio, however LOX is a cryogenic liquid fuel

with a boiling point of 90.17 K: this implies the requirement of a tank insulation layer and a limited range of materials, while nitrous oxide N₂O and hydrogen peroxide H₂O₂ are storable under standard conditions.

N₂O is the choice for relatively small rocket systems due to its self-pressurizing capability, low toxicity and cost. Self-pressurization eliminates the additional weight, complexity and cost of the pressurization or the turbopump system; it has also low emission pollutants. Conversely, N₂O presents a low density, a low specific impulse I_{sp}, and its exothermic decomposition can become difficult to control in the header injection.

Hydrogen peroxide H₂O₂ offers the advantages of: high density, ease of handling, non-toxicity, fairly high specific impulse I_{sp} and an automatic ignition. However, H₂O₂ has major safety issues due to its tendency to self-decompose.

Fuels analysed in this work are the HTPB (hydroxy terminated polybutadiene), pure or with energetic particles (aluminum, magnesium, lithium and lithium hydride), and paraffin waxes (C₅₀H₁₀₂). Thermo-physical proprieties are reported in the table below.

Solid Fuel	Average Formula	MW [g/mol]	Δh_f [kcal/mole]	ρ_f [kg/m ³]
PMMA	(C ₅ H ₈ O ₂) _n	100	-102.9	1100
HDPE	(C ₂ H ₄) _n	28	-53.8	959
HTPB	(C _{7.337} H _{10.982} O _{0.058}) _n	100	-2.97	930
Paraffin	C ₂₀ H ₄₂	282.55	-108.9	788.6

Table 1 Properties of fuel candidates for hybrid engines

The HTPB major drawback is the low regression rate and consequently unsatisfactory performance. A way to overcome this problem is to increase the heat exchange with the solid fuel matrix by means swirl injection systems and multiport grains. A substantial increase in performance can also be achieved by using nanoparticles of metal or hydrides (Al, Li, Mg, LiH).

Unlike HTPB, paraffin-based fuels have high burning rates (i.e. three times the HTPB fuels). These high regression rates of up to 4.7 mm/sec (0.185 in/sec) are due to an entrainment mass transfer mechanism along with the conventional evaporation mass transfer. Paraffin-based fuels are also inexpensive (i.e. around \$1.00/lb), processing of the fuel grains is simple; the fuel is non-toxic, non-carcinogenic, nonhazardous and environmentally friendly.

Because of its fundamental inertness, deterioration in storage is not an issue. Its safe handling property is especially important in shipping where no special precautions are needed, resulting in an appreciable cost saving. Because of the above characteristics, the paraffin-based hybrid promises to lead to a substantial cost reduction in manufacturing and operations.

A critical constraint of hybrid rocket is the low regression rate: usually to overcome this limit metallic additives in solid fuels as PB polymers and paraffin waxes are used. These additives can enhance combustion temperature, regression rate, I_{sp} and in some cases (i.e. with Al) may shift optimum performance at a lower O/F: this is beneficial in reducing the gas corrosivity and the weight of oxidizer tank.

The theoretical characteristics of the combustion products are calculated using the NASA CEA code. Performance predictions are obtained for a range of O/F ratio from 1 to 10, assuming P_c=30 bar, nozzle expansion ratio $\epsilon=A_e/A_t$ of 70 and equilibrium flow. The main parameters considered are I_{sp}, and the adiabatic chamber temperature T_c.

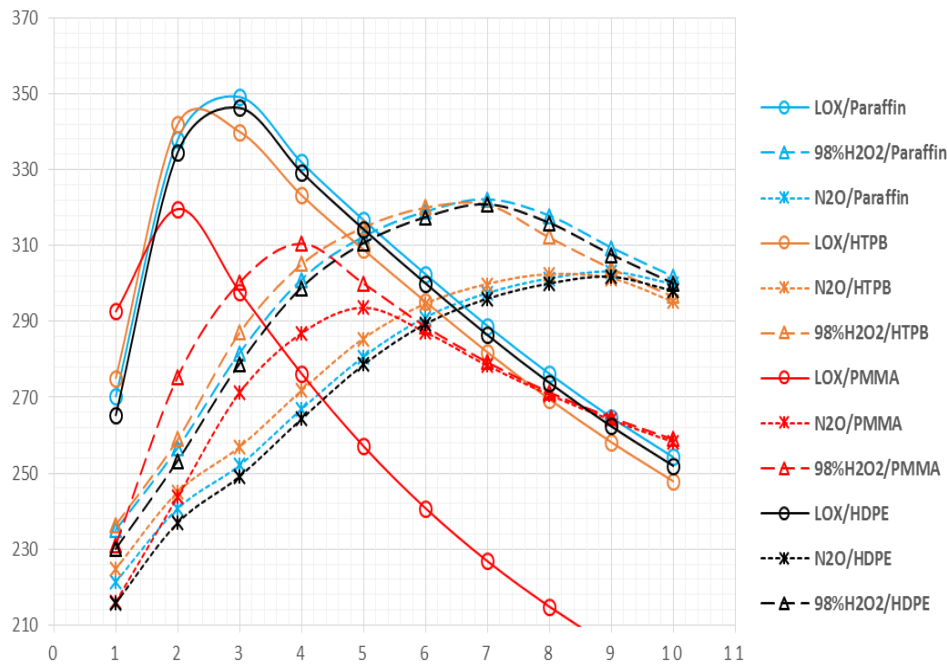


Figure 1: Isp [s] vs O/F for different propellants

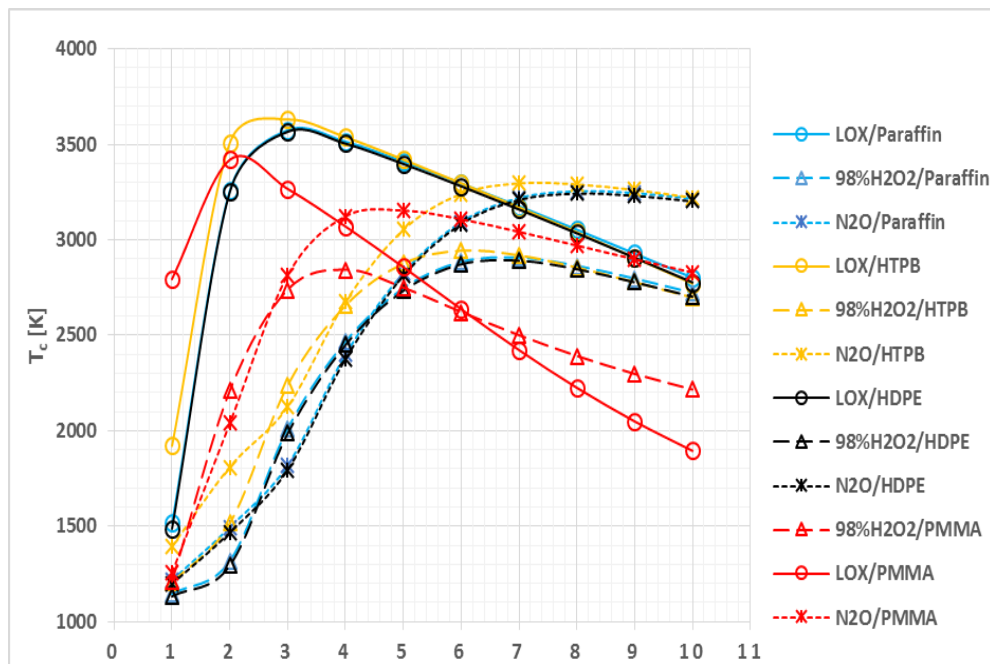


Figure 2: Tcc vs O/F for different propellants

Figure 1 and Figure 2 show the effect of O/F ratio on specific impulse I_{sp} and on flame temperature T_c . Results also show that the increase of pressure chamber P_c from 10 bar to 80 bar causes a mean change in specific impulse I_{sp} of 2-3 s for the same expansion ratio.

The variation of A_c/A_t from 25 to 70 varies the I_{sp} between 5.4% and 7.5%. The best performance are obtained with LOX, however due to the best feature of N₂O, this oxidant has been chosen.

The effects of 40% Aluminium additive in 60% Paraffin wax with N₂O and 98% H₂O₂ as oxidants (assuming $P_c=30$ bar, nozzle expansion ratio A_c/A_t of 70) has been investigated by CEA code. The I_{sp} maximum for a combination of N₂O/Paraffin is 303 s, while with a dispersion of 40% Aluminium is 311 s, and the O/F ratio

optimum shifts from 9 to 5; for a combination of 98% H_2O_2 /Paraffin without Aluminium the I_{sp} maximum is 322 s, with 40% Aluminium it is 329 s, and the O/F ratio optimum shifts from 7 to 4. The chamber temperature T_c maximum for the N_2O /Paraffin's combination increases from 3251 K without 40% Aluminium to 3551 K with 40% Aluminium, and for the 98% H_2O_2 /Paraffin's combination it increases from 2861 K to 3151K.

The most important aspect of these results is the O/F ratio's shift of about 4 point for the both Oxidant/Fuel combinations analyzed, this entails a considerable reduction of the oxidizer tank. Assuming as combination N_2O and paraffin with O/F=5, the I_{sp} is about 350 s and the thrust coefficient is 2.3.

2. The sizing of Hybrid Rockets

A matlab program has been developed to size the engine rocket^[5], the injector and the ignition system, the test bench, pressure and temperature probes.

The engine has been sized assuming the following input data.

F	230	N
I_{sp}	320	s
tb	25	s
P_c (N/m ²)	200000	Pa

The mass of the propellant m_p is calculated by:

$$\dot{m}_p = F/(I_{sp}g_0)$$

$$\dot{m}_f = \dot{m}_p/(1 + OF)$$

From the burning time possible to calculate the propellant mass required for this work. :

$$m_p = \dot{m}_p tb$$

The fuel volume is:

$$V_f = \frac{m_f}{\rho_f}$$

$\rho_{f,j}$ is the density of the fuel.

The combustion chamber mass and size depends on the fuel grain geometry. The regression rate \dot{r} for a Hybrid Rocket is defined as:

$$\dot{r} = aG_o^n$$

a , n are experimental constants depending on propellant combination, G_o is the oxidizer flow rate \dot{m}_o per unit area.

The fuel external diameter $D_{ext,g}$ for a single circular port is calculated by the integration of the regression rate \dot{r} from time $t = 0$ to $t = t_b$:

$$D_{ext,g} = \left[\left(\frac{a}{1000} \right) (4n + 2) \left(\frac{4\dot{m}_o}{\pi} \right)^n t_b + D_{int,g}^{2n+1}(0) \right]^{1/(2n+1)}$$

$$D_{int,g}(0) = \sqrt{[4\dot{m}_o/\pi G_o(0)]}$$

$D_{int,g}(0)$ is the initial port diameter of the fuel grain, and $G_o(0)$ is the initial mass flow rate of oxidant per unit area in the fuel chamber

The grain length L_g and the chamber wall thickness $t_{w,c}$ are given respectively by:

$$L_g = 4V_{f,j}/[\pi(D_{ext,g}^2 - D_{int,g}^2(0))]$$

$$t_{w,c} = (1 + f_s)P_c D_{int,c}/\sigma_c$$

$$D_{int,c} = D_{ext,g} + 2t_{ins}$$

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$$D_{ext,c} = D_{int,c} + 2t_{w,c}$$

- $t_{w,c}$ is chamber wall thickness,
- $D_{int,c}$ is the combustion chamber internal diameter,
- t_{ins} is the insulation thickness and it is assumed 0,003
- P_c is chamber pressure
- σ_c is and the yielding tensile of the chamber material
- f_s is a safety factor for the chamber wall stress, assumed as 100%,
- $D_{ext,c}$ is the fuel chamber wall external diameter

The lengths of the pre-combustion and post combustion chamber are respectively:

$$L_{pre} = 0.5D_{int,c}, L_{pos} = 0,7D_{int,c}$$

The convergence semi-angle of the nozzle is assumed $\theta_{con}=45^\circ$. The expansion rate ε and C_F are taken from the CEA code's data. Therefore the length of the nozzle convergent section is:

$$L_{con} = 0.5(D_{int,c} - D_t)/\tan\theta_{con}$$

$$D_t = \sqrt{(4A_t/\pi)}$$

$$A_t = F/(C_F P_c)$$

D_t, A_t is the throat diameter and the throat area .

The fuel chamber length L_c , and its mass m_c are calculated by:

$$L_c = L_g + L_{pre} + L_{pos} + L_{con}$$

$$m_c = 0.25\pi\rho_c[L_c(D_{ext,c}^2 - D_{int,c}^2) + t_{w,c}(D_{int,c}^2 - D_t^2)/\tan\theta_{con}]$$

ρ_c is the combustion chamber wall density .

Assuming the divergence semi-angle $\theta_{div}=13,5^\circ$, the nozzle divergent length and mass are respectively:

$$L_{div} = 0.5(D_e - D_t)/\tan\theta_{div}$$

$$m_{div} = 0.5\rho_{noz}\pi t_{w,div}(D_e - D_t) \sqrt{\frac{(D_e - D_t)^2}{4} + L_{div}^2}$$

$$D_e = \sqrt{(4A_e/\pi)}$$

$$A_e = \varepsilon A_t$$

D_e, A_e are the nozzle exit diameter and the nozzle exit area, the material of the nozzle is assumed the same combustion chamber, then $\rho_{noz} = \rho_c$, $t_{w,div} = 0.5t_{w,c}$ is the average nozzle wall thickness.

Results of the sizing consists in a whole engine of 266 mm in length with a diameter of 60 mm. It is made of a precombustion chamber, a combustor and a post combustion chamber. Four fuel injectors introduce N₂O into the combustion chamber with a O/F mixture fraction of 5. The injectors diameter is 1.3 mm each.

Input parameters		
Isp	320,00	s
F	230,00	N
Tb	25,00	s
Pc (N/m ²)	2000000,00	Pa
OF	5,00	
CF	1,43	
a	0,17	
n	0,50	
gamma	1,13	

HRE GEOMETRY		
mp'	0,073	kg/s
mfu'	0,012	kg/s
mox'	0,061	kg/s
Mp	2,16	kg
Mox	1,80	kg
Mfu	0,36	kg
Dint,g	0,012	
Dext,g	0,06	
Lg	0,10	
Lpre	0,04	

Lpos	0,06	ε	10,00
Lcon	0,04	De	0,03
θcon	45,00	Ldiv	0,05
Dt	0,01	θdiv	13,50
Lc	0,27		

A figure of the combustor geometry is shown in Fig.4.

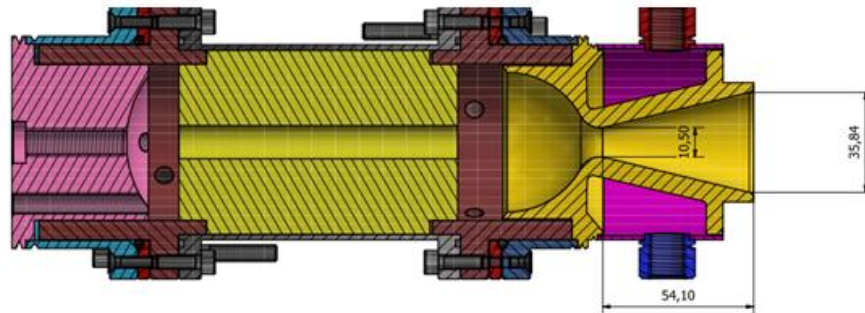


Figure 3 View of the combustor geometry

Figure 4 shows a simplified diagram of the main components of a test bench for hybrid engine on laboratory scale with probes of temperature, pressure and thrust.

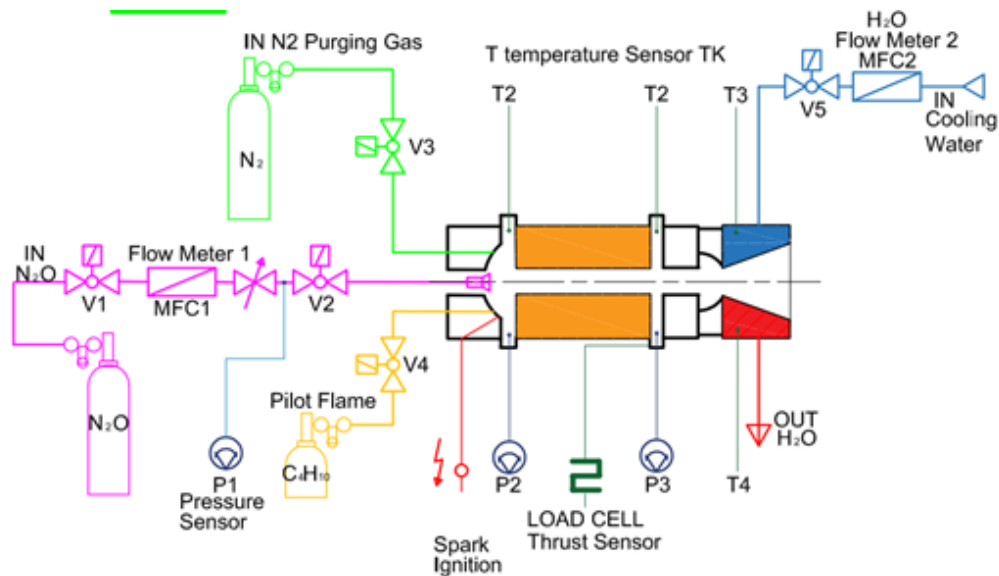


Figure 4: Block scheme of the main components of the test bench

A cooling system for the nozzle has been provided to cool the throat and also to measure the water heating. The ignition system consists of a pilot C₄H₁₀/N₂O pilot flame ignited by a spark. A N₂ system has been also considered for the purging of the engine at the beginning and at the end of the test.

3. Numerical Simulations

In order to better understand the behavior of the flow inside the combustion chamber in terms of pressures, temperatures, mixing and flame anchoring, 3D RANS simulations have been performed for different port grain

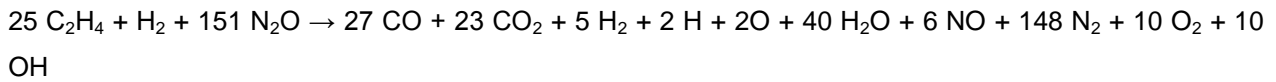
diameters, starting from 0.012 to 0.020 by means of the commercial code Fluent®16 Ansys code. The RANS simulations have been performed assuming a pressure-based formulation, 2nd order for all variables. The turbulence model adopted is the standard k-ε Realizable model, the turbulence/chemistry coupling is assumed the Eddy Dissipation Concept model. Since pressures are not really high, an ideal gas model has been implemented. As for the boundary conditions, N₂O is injected at 20 atm and 290 K in a gaseous state by means of 4 injectors of 1.3 mm diameter. In order to reduce computational times, paraffin is assumed to be injected at the evaporating temperature of 725 K by means of a mass flow inlet condition.

In fact, assuming melting times lower than kinetic times, it is possible to state that paraffin reacts with N₂O in a gaseous phase.

The paraffin cracking mechanism may be simplified in a one step reaction:



where paraffin decomposes mainly in C₂H₄. Therefore a mixture of hydrogen and ethylene is injected into the combustion by the paraffin internal boundaries. A one step reaction has been implemented in the code to simulate paraffin/N₂O gaseous reaction.



3.1 Geometry and Mesh

The HRE geometry includes the injector plate, pre-combustion, combustion and post-combustion chamber and convergent-divergent nozzle (see Fig. 6).

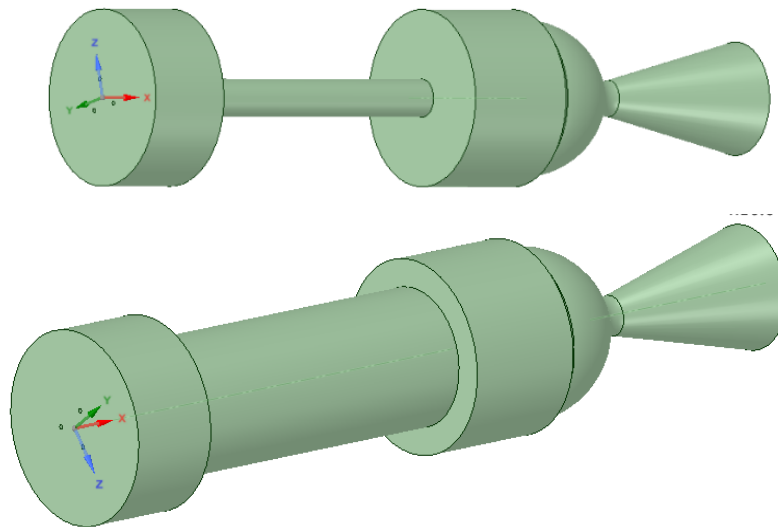
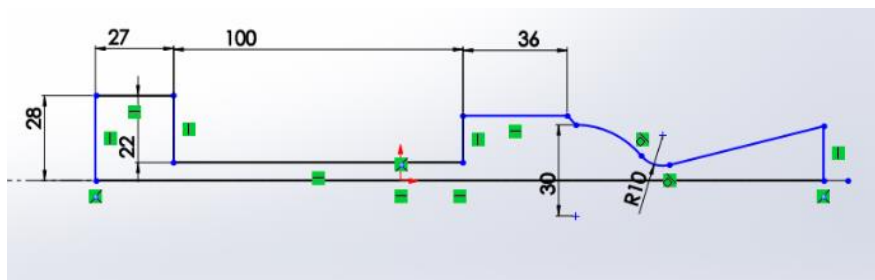


Fig 6 3D Geometry with port diameter 12mm and 40mm

In Fig. 7, a 2D Geometry with port diameter 12mm and 40 mm is shown.



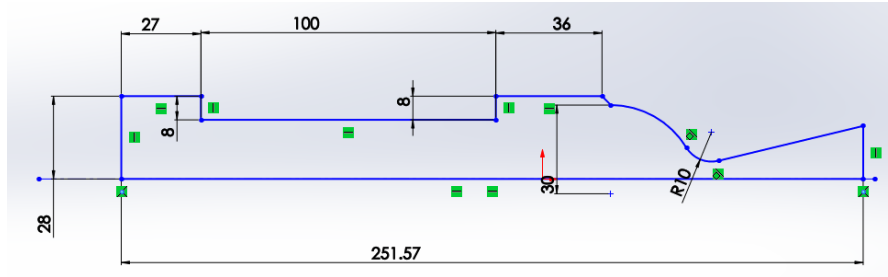


Figure 7: 2D Geometry with port diameter 12mm and 40mm

The combustor geometry of Fig. 6 has been mapped by a three 3-D grids fully unstructured grid respectively of 2.4M cells and 3.4 Mcells.

4 Results

Numerical results show that assuming the lower diameter, an overpressure is verified in the precombustion chamber reaching 56 bar (see Fig. 8 and 9). Pressure starts to decrease linearly in the combustion chamber, reaching the theoretical value of 18 bar in the post combustion chamber. For this reason a check valve is mandatory to avoid a back flow in the N₂O line.

The outlet pressure is lower than ambient pressure, therefore, the nozzle will work on ground in over expanded conditions.

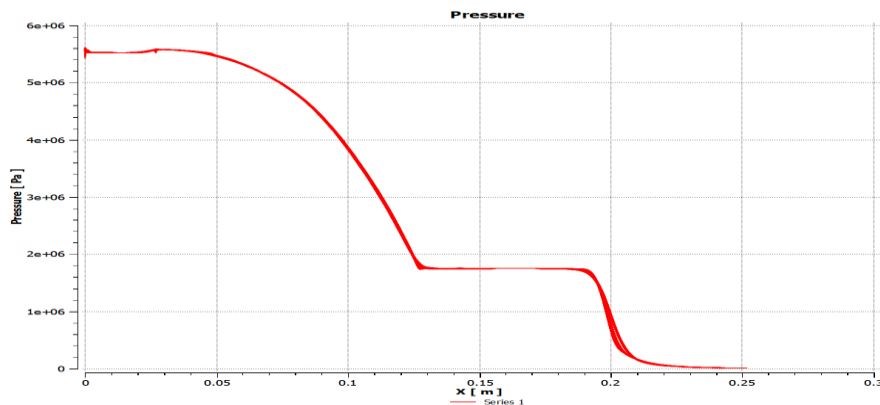


Figure 8: Average pressure along the HRE axes(port diameter 12mm)

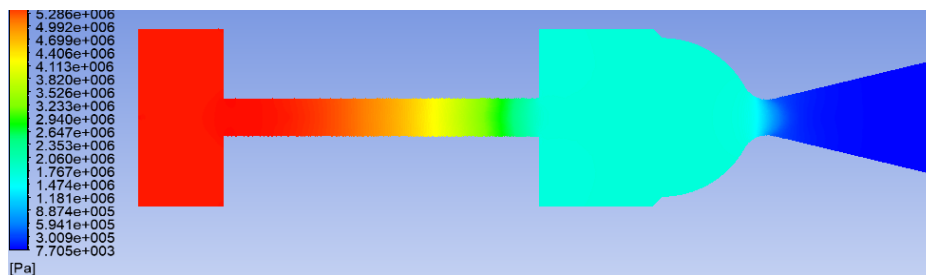


Figure 9: Pressure flowfield (port diameter 12mm)

Fig. 10 and 11 show that N₂O is completely decomposed after 75 mm from the injection in O₂ and N₂ as shown also in fig 12 and Fig. 13.

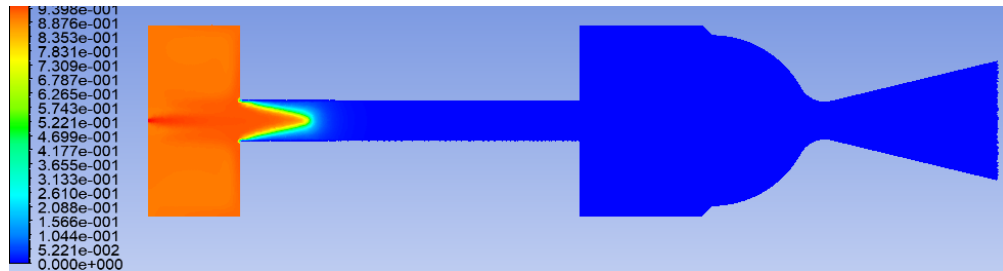


Figure 10: N₂O flowfield (port diameter 12mm)

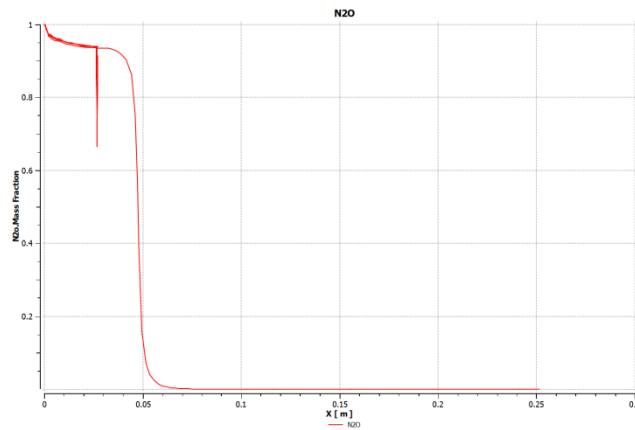


Figure 11: Average N₂O mass fraction along the HRE axes (port diameter 12mm)

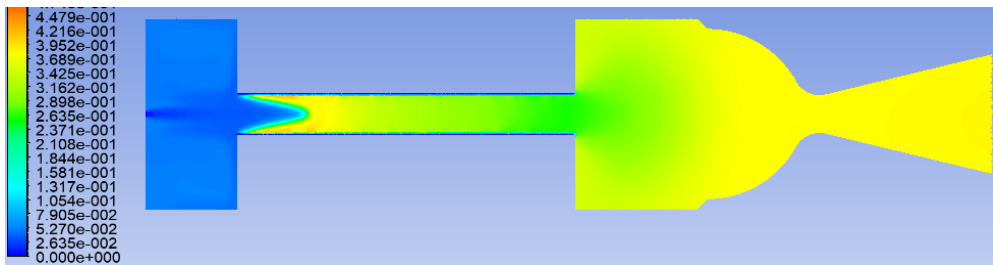


Figure 12: N₂ flowfield (port diameter 12mm)

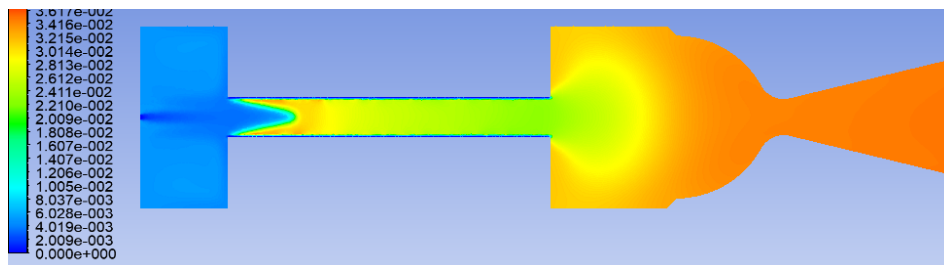


Figure 13: N₂ flow field (port diameter 12mm)

Fig. 14 shows that H₂O keeps constant after its formation and increases slightly in the post combustion chamber. Temperature increases to an average temperature of 1200 K at 50 mm and then keeps constant within the grain hole. Entering in the post combustion chamber, temperature decreases to 800 K due to the flow expansion and

then starts again increasing to 1400 K due the combustion as shown in Fig. 14. The rapid temperature decrease could produce a solidification of paraffin yielding problems to the engine. In fact, residence time could be comparable to melting time, while, in the nozzle, the flow velocity is high enough to avoid this problem. In the nozzle, the temperature expands increasing the flow velocity to Mach 3.5 assuming ideal conditions.

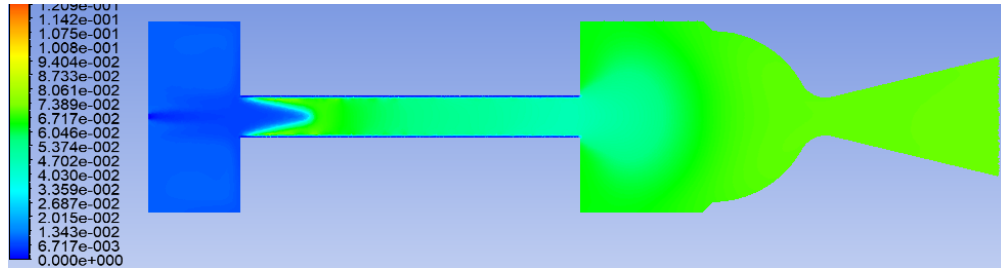
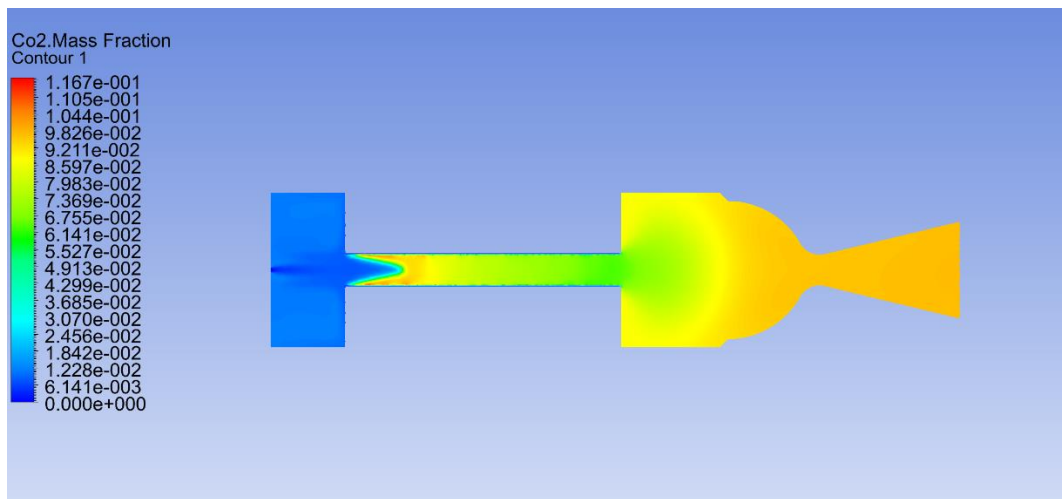
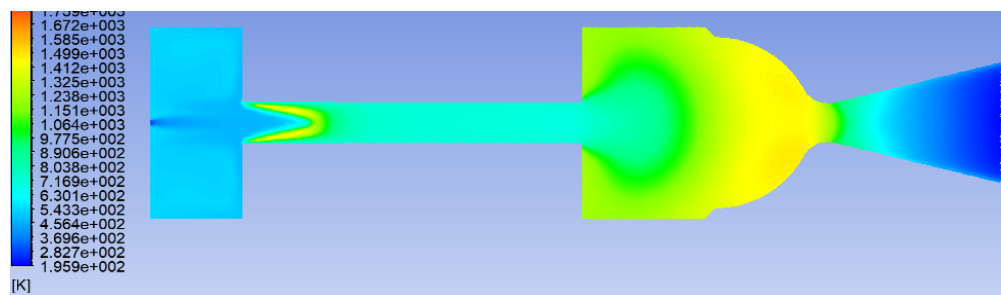
Figure 14: H₂O flowfield (port diameter 12mm)Figure 15: CO₂ flowfield (port diameter 12mm)

Figure 16: Temperature flowfield (port diameter 12mm)

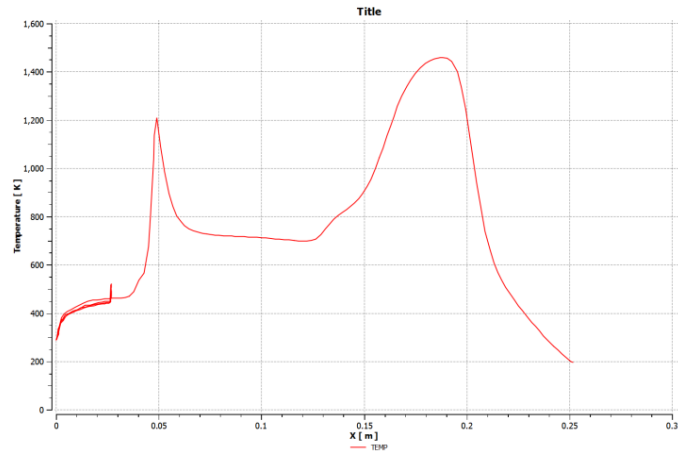


Figure 17: Average Temperature along the HRE axes (port diameter 12mm)

Increasing the port diameter to 40 mm, the pressure within the combustion chamber keeps constant at 22 bar. For the given propellants mass flow rate of 90 g/s, a pressure 10% higher than theoretical results is predicted by numerical simulations (see Fig. 18 and Fig. 19).

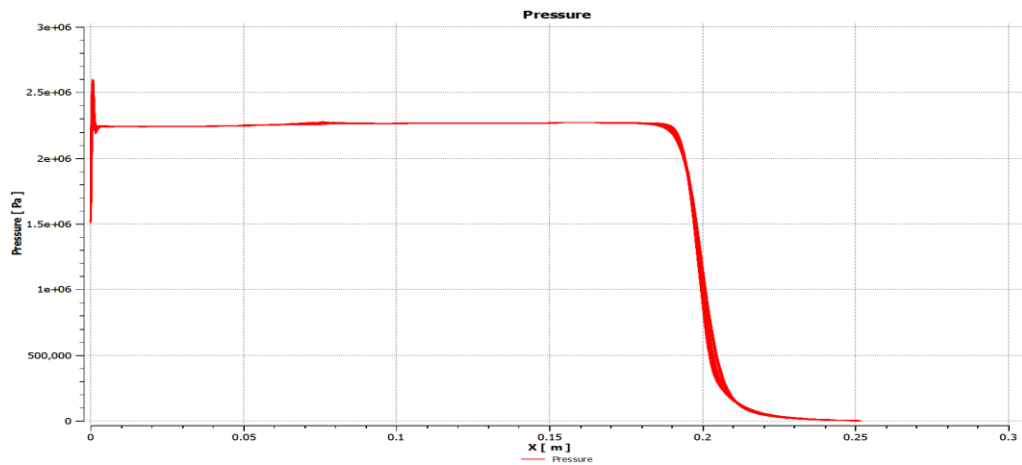


Figure 18: Average pressure along the HRE axes (port diameter 40 mm)



Figure 19: Pressure flowfield (port diameter 40 mm)

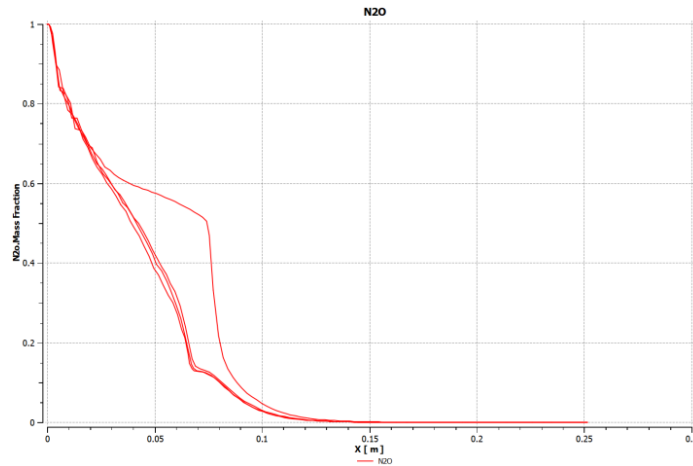


Figure 20: Average N2O along the HRE axes (port diameter 40 mm)

Fig. 18 shows that N₂O is completely decomposed after 140 mm from the injection in O₂ and N₂.

3. Conclusion

Numerical simulations of different grain port diameters have been performed in order to verify the different conditions in the combustor chamber. Two dimensions have been selected: 12 and 40 mm. Results show that numerical simulations are a useful tool to preliminary design and verify critical conditions within the combustor. Numerical simulations predict a overpressure in the precombustion chamber and a weak flame anchoring when the port diameter is 12. Also the smaller port diameter causes an expansion of the flow when entering the post combustion chamber, this causing the flow solidification. Furthermore, numerical results allowed for the set up of the experimental test bench.

3. References

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