

INJECTOR AND COMBUSTION CHAMBER DESIGN FOR A NITROUS OXIDE AND ETHANOL ROCKET ENGINE

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Abstract. The basic design of a rocket engine injector and combustion chamber for saturated nitrous oxide and liquid ethanol is presented. At first, an oxidant-fuel mixture is selected based on a thermochemical analysis that explores several existing options and other combinations that have not yet been studied. As a result, nitrous oxide is chosen as an oxidant and ethanol as fuel. Then a simplified methodology is proposed for the design of a pressure-swirl injector responsible for ethanol. Computational fluid dynamics is used to verify the validity of the above-mentioned analysis, using Volume of Fluid (VOF). For the nitrous oxide injector, the flash-boiling phenomenon is investigated, verifying its importance for the ongoing project. The effect is treated analytically using the Dyer model to account for non-equilibrium thermodynamics. Simplified zero-dimensional and one-dimensional combustion models are explored as tools to design the rocket combustion chamber. Furthermore, combustion instability due to acoustic phenomena is studied, with the first spinning tangential mode being computed for the herein developed motor and an ensemble of acoustic cavities being developed to suppress the aforementioned mode. Finally, a diagram of the static test bench which will be used to validate the injectors and the designed engine is also presented.

Keywords: Liquid rocket motor, Injector, Combustion, Instability, Acoustic cavity.

1. INTRODUCTION

The aerospace sector has been growing in the past years with the introduction of new private-owned companies exploring this market that was previously dominated by governments. With an increasing demand for satellite communication, especially for small satellites, it becomes increasingly more important to own technology to put those satellites in orbit. Rocket engines are one of the main components needed to achieve this goal and, therefore, developing this type of technology will be essential in the near future.

This type of engine has a key component that admits the propellant into the chamber for combustion to occur: the injector. It plays a fundamental role in combustion efficiency, and therefore is crucial on the performance of a liquid-propellant engine. Combustion chamber geometry also plays a fundamental role. An optimized length is needed to guarantee fuel droplets evaporate and burn before reaching the nozzle, while chamber volume has a direct impact in combustion instability.

The present work is part of Project NOELLE (Nitrous-Oxide EthanoL Liquid Engine), whose goal is to design, build and test a small-scale rocket engine prototype with saturated nitrous oxide and liquid ethanol as propellants. The project is subdivided into two main areas: injector and combustion chamber design, presented here, and nozzle and regenerative cooling design, presented in another article. Figure (1a) shows a rendering of Project NOELLE's engine, displaying a the nozzle and combustion chamber, built out of copper. Behind the combustion chamber, the fuel and oxidizer injector can be seen. Figure (1b) shows the injector in more detail.

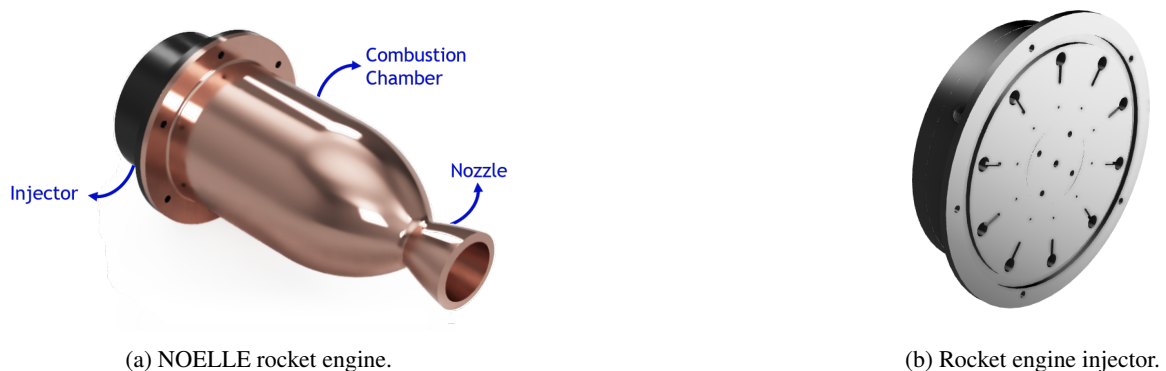


Figure 1: NOELLE's rocket engine and injector renderings.

The injector and combustion chamber are designed to be well suited for a rocket engine prototype with the following

requirements:

- Engine nominal thrust: 3000 N for 5 s;
- Combustion chamber operating pressure: 1 bar to 15 bar;
- Propellant tank operating pressure: 55 bar to 70 bar.

While liquid rocket engines are common in the literature, ethanol - nitrous oxide engines are rather rare and are yet to be implemented as a finished product. Tokudome *et al.* (2007) is one of the first published studies to present an operational engine using these propellants. Static-fires were performed achieving 700 N of thrust using like-impinging doublet injectors for both propellants and a gaseous hydrogen - gaseous oxygen torch igniter. While this engine was used as a small scale prototype for further development, Kakami *et al.* (2010) designed and tested a much smaller engine with a nominal thrust of 1 N, geared towards small satellites. Besides the different scale, Kakami *et al.* (2010) proposed a plasma assisted combustion model, demonstrating its viability.

More recently, Phillip *et al.* (2016) developed a modular ethanol - nitrous oxide engine and the necessary infrastructure to conduct further research in the future. Even though the design is similar to Tokudome *et al.* (2007) in scale and ignition/injection methods, significantly higher efficiencies were achieved. Important theoretical contributions were also made by Palacz (2017) who showed how an ethanol - nitrous oxide engine holds potential for future applications. Among them are launcher vehicles upper stages, storable military units and propulsion for small satellites.

This article starts by describing the methodology used to compare different fuel-oxidizer mixtures on the basis of specific impulse, density and cost, demonstrating how ethanol and nitrous oxide constitute a viable candidate. The methodology is followed by a high-level analysis of rocket motor design in Section 2, which forms the basis of the following Sections. Then, four independent Sections describe the details of the ethanol (Section 3) and nitrous oxide injectors (Section 4), as well as combustion modeling (Section 5) and instability analysis (Section 6). Finally, an overall injector and combustion chamber assembly is presented in Section 7, and a method to safely test the proposed systems via a static fire is described.

2. ENGINE DESIGN

Three major constraints are considered in the early stages of propulsion system design: thrust, chamber pressure and ambient pressure. Once these are set and the propellant is chosen, it is possible to compute the main parameters of a rocket engine.

In order to select an appropriate oxidizer and fuel pair, several conditions were considered. One relevant parameter taken into account was the specific impulse, I_{sp} , which is defined as the ratio between thrust T and the sea level weight rate of propellant consumption at a given instant of time, $\dot{m}_p g_o$, as follows:

$$I_{sp} = \frac{T}{\dot{m}_p g_o} \quad (1)$$

Therefore, I_{sp} can be seen as a merit of propellant efficiency. Figure (2) displays the specific impulse of several candidate oxidizer-fuel pair considered as a function of its density, for a wide range of oxidizer-to-fuel mass ratio.

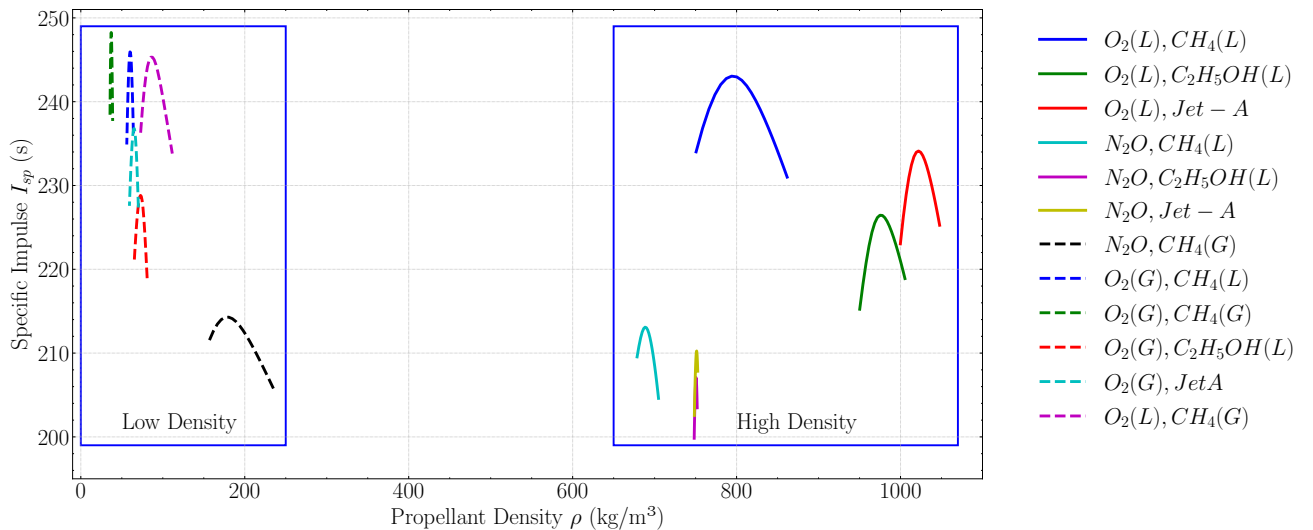


Figure 2: Specific impulse of all considered oxidizer-fuel combinations.

Although some combinations provide a substantial advantage in terms of specific impulse, they fell out of favour due to the comparatively higher difficulty in purchasing one or both of the components. This is the case of propellants including JetA, Liquid Oxygen and Liquid Methane, that were only found to be sold in extremely large amounts, usually to industries.

Moreover, it was later decided not to use any gaseous substance, since these lead to comparatively low energy density, which in turn make the use of the respective rocket engine prohibitive due to overall weight concerns.

Therefore, it was decided to proceed with a nitrous oxide and ethanol powered rocket motor. Among their advantages, it is worth noting the self-pressurization properties of the Nitrous Oxide (which dismisses the need for additional pressurization devices) and the low freezing point of Ethanol, which makes it suitable for regenerative cooling the nozzle.

Considering the use of nitrous oxide (N_2O) as oxidiser and liquid ethanol ($\text{C}_2\text{H}_5\text{OH}(\text{L})$) as fuel, the rocket engine was simulated employing a code developed by Ceotto *et al.* (2020), based on NASA Chemical Equilibrium with Applications (NASA CEA) program output and available at GitHub. A fuel to oxidiser equivalence ratio of 1.5 was considered to yield a low adiabatic chamber temperature. The resulting quantities obtained can be analyzed in Table (1).

Table 1: Specified and calculated rocket engine parameters using N_2O as oxidizer and $\text{C}_2\text{H}_5\text{OH}(\text{L})$ as fuel.

Parameter	Value	Unit
Adiabatic chamber temperature	2938.2	[K]
Ratio of specific heats of exhaust products	1.17	-
Oxidiser/fuel mass ratio	3.52	-
Specific impulse	216.66	[s]
Total mass flow rate	1.411	[kg/s]
Oxidiser mass flow rate	1.099	[kg/s]
Fuel mass flow rate (injector)	0.209	[kg/s]
Fuel mass flow rate (film cooling)	0.104	[kg/s]
Nozzle throat diameter	43.3	[mm]
Nozzle exit diameter	75.8	[mm]

It must be pointed out that the fuel chosen was later modified to be a mixture of ethanol and water, with 92% by mass of ethanol and 8% of water, in order to enhance the convection heat transfer coefficient and enable proper regenerative cooling of the nozzle. Moreover, some of the fuel will be injected to sustain film cooling: this portion of the fuel was not considered when designing the ethanol injector.

3. ETHANOL INJECTOR DESIGN

For the single-phase flow of ethanol, the pressure-swirl atomizer was deemed more suitable than the others, mainly due to its wide range of applications, to the extensive available literature and to its characteristic low discharge coefficient, as stated by Lefebvre and McDonell (2017), which allows for a great pressure drop (essential to ensure proper liquid breakup). In this type of injector, the high-pressure liquid enters a spin chamber through tangential inlet ports. As a result, the fluid not only has an axial velocity component but also a tangential velocity component, which leads to a swirling motion and to the emergence of an air-core. It then proceeds to the exit orifice, forming a thin liquid sheet that disintegrates as it leaves the atomizer, in a conical shape: it becomes unstable and breaks up into droplets.

The inviscid analysis from the work of Giffen and Murszew (1953) yields useful and somewhat accurate relationships between performance and geometric parameters, and thus was the cornerstone for the preliminary design of the ethanol injector. Starting from the principle of conservation of angular momentum, assuming incompressible, irrotational and stationary flow, and making the size of the air core such that the maximum flow rate possible is achieved, the equation for the discharge coefficient is derived:

$$C_d = A \sqrt{\frac{(1 - X)^3}{(1 + X)}} \quad (2)$$

Where A is a correction coefficient. According to Giffen and Murszew (1953), $A = 1.17$. X is given by:

$$X = \frac{A_e}{A_o} \quad (3)$$

Where A_o is the exit orifice area and A_e is the area of the air core at the exit.

In order to more accurately predict the performance of the ethanol injector, a numerical simulation was carried out using the Volume of Fluid (VOF) method, on ANSYS Fluent software. The goal was to precisely track the injector's air-core, thus validating the analytical model proposed by Giffen and Murszew (1953).

To simulate the internal flow inside the pressure-swirl atomizer, the axisymmetry of the problem was taken into account and therefore a 2D mesh was made. The inlet was constructed as an edge of length equal to the inlet ports diameter. The flow was treated as laminar: in Maly *et al.* (2019), the laminar model provided results with good agreement to experimental data, and thus was deemed suitable. The volume fraction of ethanol obtained after the system approached this apparent steady state is shown in Figure (3), which mirrors the simulation domain for visualization purposes.

The spray cone half-angle obtained was approximately 30° , in contrast with the 41° predicted by the analytical model. Furthermore, the film thickness at the orifice exit was approximately 0.502 mm, which is very close to the expected 0.495

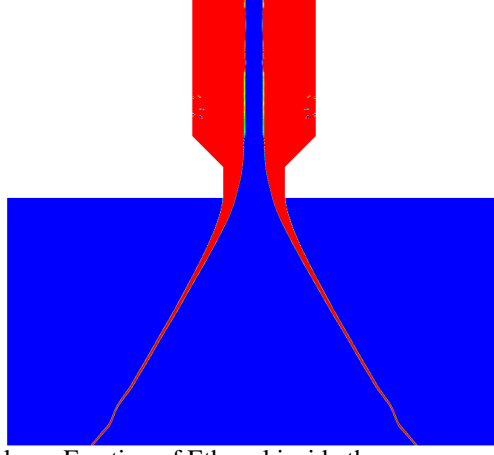


Figure 3: Volume Fraction of Ethanol inside the pressure-swirl atomizer

mm. Total inlet pressure simulated was 48.2 bar, which results in a discharge coefficient of approximately 0.5026, versus 0.5067. Therefore, a large deviation was observed only for the spray half-cone angle. This discrepancy is probably due to viscous effects on the numerical simulation, which tend to decrease the swirl velocity, and hence the cone angle. Table 2 summarises the comparison between the analytical model and the VOF simulation.

Table 2: Comparison between predictions of the analytical model and the VOF simulation

Model	Analytical	VOF Simulation	Deviation
Discharge coefficient	0.5067	0.5026	0.8%
Film thickness (mm)	0.495	0.502	1.4%
Spray cone half-angle (degree)	40.1	30	25%
Total inlet pressure (bar)	47.4	48.2	1.7%

4. NITROUS OXIDE INJECTOR

The phenomenon of flash-boiling must be taken into account to guarantee a correct design of the nitrous oxide injector. Since nitrous oxide is subcritical at room temperature, the pressure drop along the injector is usually sufficient to vaporize the chemical compound. This leads to difficulties in computing the actual mass flow rate across the injector, arguably the most important requirement to fulfill.

Nevertheless, considerable effort from the scientific community has been put into developing trustworthy analytical models, which can be used in the preliminary phase of design. Along with experimental data, these models can accurately predict, up to an extent, the mass flow rate across a nitrous oxide injector. An example of such model is the one presented by Dyer *et al.* (2007), later corrected by Solomon (2011). The total mass flow rate across the injector is defined as a balance between the mass flow rate considering single incompressible fluid ($\dot{m}_{SPI}$) and the mass flow rate considering thermal equilibrium between liquid and vapour phase ($\dot{m}_{HEM}$). It is written in the following fashion:

$$\dot{m} = \frac{k}{1+k} \dot{m}_{SPI} + \frac{1}{1+k} \dot{m}_{HEM} \quad (4)$$

The mass flow rate $\dot{m}_{HEM}$ corresponds to the Homogeneous Equilibrium Model, which takes into account the critical downstream pressure, where the flow becomes "choked", i.e. mass flow rate reaches a maximum value. It is defined as:

$$\dot{m}_{HEM} = C_d A \rho_2 \sqrt{2(h_1 - h_2)} \quad (5)$$

Where h_1 and h_2 are the upstream and downstream values of enthalpy for the nitrous oxide, respectively, considering a vapor fraction-weighted average (or vapor quality-weighted average). This fraction (or quality) is computed by assuming isentropic flow across the injector. However, $\dot{m}_{HEM}$ is not sufficient to describe the flow, because thermodynamic equilibrium might not be attained since liquids can exist below their vapor pressure if no nucleation sites are available for bubble initiation Dyer *et al.* (2007). Therefore, the mass flow rate for incompressible liquid $\dot{m}_{SPI}$, given by the standard equation for the discharge coefficient, must be considered. The balance between the two is ensured by the parameter k , which is a ratio between bubble growth time τ_b and residence time τ_r of the liquid inside the injector, as follows:

$$k = \frac{\tau_b}{\tau_r} = \sqrt{\frac{P_1 - P_2}{P_v - P_2}} \quad (6)$$

Where P_1 and P_2 are the nitrous oxide upstream and downstream pressures, respectively, and P_v is its vapour pressure. It can be inferred that, if the flow spends little time inside the injector and bubbles grow quickly, a thermodynamic equilibrium model is not feasible. In this case, k gets big, and thus the mass flow rate term $\dot{m}_{HEM}$ becomes negligible, as expected.

Nevertheless, this model does not account for the ratio between length and diameter of the orifice (L/D). As this ratio increases, the flow has more time to reach thermodynamic equilibrium, and therefore the Homogeneous Equilibrium Model dictates the mass flow rate, as shown by Henry and Fauske (1971). Hence one should be careful when designing injectors with high or low L/D ratios using the aforementioned model.

A nonimpinging (or shower head) injector was chosen for the nitrous oxide since good agreement between the proposed model and experimental data was found by Dyer *et al.* (2007) for simple orifice injectors.

Assuming all orifices have diameter of 1.5 mm and taking C_d as 0.66 from Dyer *et al.* (2007) for this orifice size, it was possible to compute the number of orifices required to attain the desired mass flow rate: ten. CoolProp by Bell *et al.* (2014) was used for retrieving nitrous oxide properties.

5. COMBUSTION MODELING

Inside the combustion chamber, ethanol droplets will mix with gaseous nitrous oxide due to flash boiling. The high-temperature ambient will cause the droplets to vaporize. Ethanol vapor then reacts with nitrous oxide generating heat. When designing a combustion chamber, two objectives must be considered: it is crucial that almost every droplet fully vaporizes before reaching the nozzle, however, a significant proportion of them should not vaporize too close to the injector plate, since it is not cooled and could melt if intense combustion takes place near its surface (Spalding (1959)). This balance can be attained by selecting a combination of combustion chamber diameter and length which vaporizes a droplet of average diameter near the center of the chamber.

Therefore, in order to conduct a preliminary design of a rocket combustion chamber, knowledge about droplet vaporization, fuel-oxidizer mixing and combustion is needed. While CFD and even DNS are increasingly more relevant for combustion chamber design, the computational infrastructure available to the authors made their use impractical considering the scope and duration of this work. However, simplified zero-dimensional and one-dimensional models are sufficient to compute a suitable combustion chamber diameter-length pair (Belal *et al.* (2019)).

Since no specific reaction mechanism is available for the combustion of ethanol with nitrous oxide, a short description of how the mechanism used for the following combustion studies is presented first. Then, a chemical reactor network is developed to model droplet evaporation and combustion along the combustion chamber and nozzle.

5.1. Reaction Mechanism

While experimental studies on combustion characteristics of ethanol, C_2H_5OH , and nitrous oxide, N_2O , mixture have been conducted (Lee *et al.* (2014)), no chemical reaction mechanism has been created and validated for such fuel-oxidizer pair. Since a thorough mechanism investigation is out of scope for this work, an alternative is to combine reaction mechanisms used for ethanol-air combustion (Marinov (1999); Saxena and Williams (2007); Cancino *et al.* (2010)) with nitrous oxide decomposition mechanisms (MONAT *et al.* (1977)). Another option would be to add an ethanol sub-mechanism into a hydrocarbon combustion mechanism which already contains nitrous oxide and related species, such as (Smith *et al.* (2000)) which has already been used when nitrous oxide was the oxidizer (Wang *et al.* (2020)), or (Mével *et al.* (2009)) which proposes a mechanism for hydrogen-nitrous oxide combustion. To evaluate the best options, three new mechanisms for ethanol-nitrous oxide combustion were created.

The first one is based on the San Diego Mechanism described by Saxena and Williams (2007), which is used for combustion simulations of several hydrocarbons, including ethanol. Since the San Diego Mechanism also provides a sub-mechanism for nitrogen species which include nitrous-oxide, this sub-mechanism is combined with the original mechanism to achieve the desired result. The second mechanism created combines the work of Marinov (1999) as an ethanol mechanism with results from Mével *et al.* (2009), which serves as a sub mechanism for nitrous-oxide and other nitrogen based compounds. The last mechanism is also based on Marinov (1999) for the ethanol mechanism. However, nitrous-oxide decomposition is based on the nitrogen sub-mechanism from Smith *et al.* (2000), which includes not only nitrogen and oxygen equations but also nitrogen-carbon and nitrogen-hydrogen.

Table (3) provides a summary comparing the proposed mechanisms. In general, all three reaction mechanisms come from different bases. All mechanism files can be found at (Ceotto *et al.* (2020)). To compare them and attempt to analyse their validity, the ignition delay in an ideal gas constant-pressure fixed-mass reactor is calculated. A constant pressure reactor is chosen so that the rocket's combustion chamber pressure can be used in this analysis.

Table 3: Proposed mechanism comparison.

Identification	San Diego	Marinov + Mevel	Marinov + GRI
Hydrocarbon mechanism	San Diego	Marinov	Marinov
NOX mechanism	San Diego	Extracted from Mevel	Extracted from GRI 3.0
Species	68	93	75
Reactions	311	664	494
Ignition delay	9.2 μs	4.6 μs	6.5 μs

The reactor considers a completely homogeneous systems, meaning that a single value of each variable is needed to

describe the entire volume of the reactor. The governing equations of this reactor (Turns (1996)) are ordinary differential equations which describe the evolution of reactor temperature, T , and species mass fractions, $[X_i]$:

$$\frac{dT}{dt} = \frac{\sum_i (\bar{h}_i \dot{\omega}_i)}{\sum_i ([X_i] \bar{c}_{p,i})}, \quad (7)$$

$$\frac{d[X_i]}{dt} = \dot{\omega}_i - [X_i] \left[\frac{\sum_j \dot{\omega}_j}{\sum_j [X_j]} + \frac{1}{T} \frac{dT}{dt} \right], \quad (8)$$

where $\bar{h}_i$ is the molar enthalpy and $\dot{\omega}_i$ is the molar production rate of species. The latter is given by the reaction mechanisms as a function of species concentration. The molar heat capacity of the mixture is given by $\sum_i ([X_i] \bar{c}_{p,i})$.

This forms an initial-value problem which can be integrated in time to result in the evolution of an initially premixed mixture of fuel and oxidizer. The reactor was simulated using Cantera (Goodwin *et al.* (2018)) and all three mechanisms considered an initially stoichiometric mixture at 15 bar and 1500 K. The temperature evolution for each mechanism is shown in Figure (5a), while (3) summarizes the results. Even though the results are different, all three mechanisms resulted in an ignition delay of the order of 10^{-5} s. This and the fact that these values are reasonable for ignition delays when nitrous oxide is used as the oxidizer (Mével *et al.* (2009)) supports the mechanisms proposed.

5.2. Chemical Reactor Network

Once inside the combustion chamber, ethanol droplets are expected to have a lifetime orders of magnitudes greater than the characteristic combustion time scale, which should have a similar order of magnitude as the ignition delay presented previously (Spalding (1959)). Thus, the one-dimensional vaporization-controlled combustion reactor described by Turns (1996), which assumes the gas phase inside the combustion chamber is always in chemical equilibrium while the fuel droplets are evaporating, can be used to predict the length needed to vaporize most droplets.

After all droplets have been completely vaporized, the remaining part of the combustion can be modeled as a traditional plug flow reactor (Turns (1996)). Furthermore, the rocket's nozzle can also be decomposed into two varying-area plug flow reactors for the converging and diverging parts, respectively, allowing for the study of reactive flow rather than having the usual frozen flow or equilibrium assumption used in common codes (Gordon and McBride (1994)). These reactors can be simulated in series, forming a chemical reactor network (Figure 4) capable of expressing the behavior of important quantities along the combustion chamber axis, such as gas temperature and Mach number.

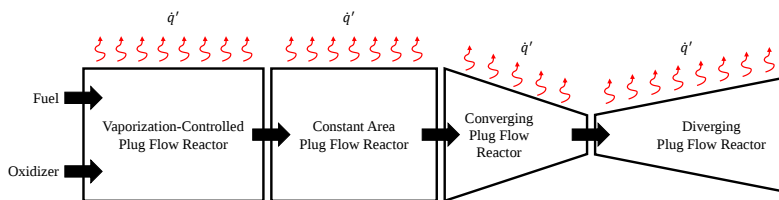
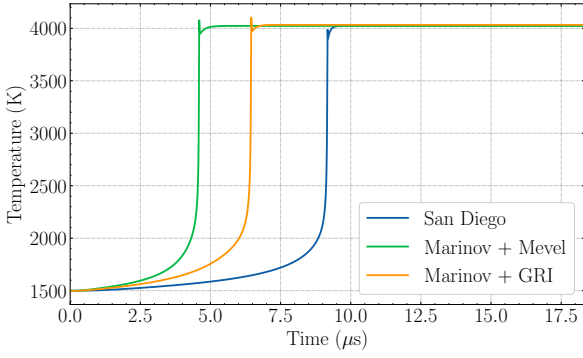


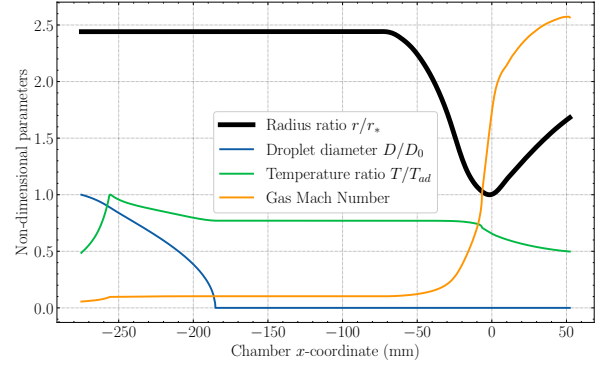
Figure 4: Reactor Network Model for a combustion chamber - nozzle system.

Such chemical reactor network is, mathematically speaking, a set of initial value problems. This model has been implemented (Ceotto *et al.* (2020)) in Python and solved using SciPy's integration routines. Cantera was once again used to calculate thermodynamic equilibrium and reaction rates, employing the **Marinov + Mevel** mechanism described before.

Figure 5b shows the evolution of the droplet diameter D , gas phase temperature, T and Mach number along the chamber and nozzle length. While the diameter is divided by the initial droplet diameter (SMD), the temperature is normalized by the adiabatic stoichiometric flame temperature. The radius $r(x)$ of the chamber is also shown, divided by the nozzle throat radius r_* . This occurs at $x - x_0 = 91.5$ mm after the injector plate, which shows that the selected combustion chamber length of $L = 200$ mm would be sufficient for complete droplet evaporation and combustion. The graph also shows how the temperature peaks near $x - x_0 = 20$ mm. This occurs when the equivalence ratio of the mixture becomes one. For larger values of x , more ethanol vaporizes increasing the equivalence ratio and creating a rich mixture. Therefore, the temperature starts to drop again. Approaching the nozzle, compressible flow becomes more significant and the typical acceleration provided by choked nozzles can be observed in the Mach number.



(a) Ignition delay considering a constant pressure reactor with an initial stoichiometric mixture at 1500 K.



(b) One-dimensional vaporization controlled combustion model results.

Figure 5: Combustion analyses used in this work.

6. COMBUSTION INSTABILITY

The understanding and forecast of combustion instabilities are of utmost importance in the development of liquid rocket engines. If not properly assessed, they can lead to severe pressure vibration forces, which can blow the engine apart. In order to address the problem, engineers must properly design combustion chamber, injection systems and feed lines, among others, adding (or removing) features with the goal of preventing instabilities from occurring.

According to Sutton and Biblarz (2016), combustion instabilities can be divided into three types, according to the respective frequency range: chugging (10-400 Hz) is related to possible pressure and mass flow disturbances on the propellant feed lines; buzzing (400-1000 Hz) is caused by coupling between the combustion process and flow on the propellant feed system; screeching (or screaming, above 1000 Hz) is related to the development of unstable pressure waves inside the combustion chamber.

The latter is the most damaging type, since it carries the most energy. It is capable of being utterly destructive in a matter of seconds. This high-frequency instability manifests itself in acoustic longitudinal vibration modes (parallel to the combustion chamber axis) and transverse vibration modes (radial and tangential modes).

These acoustic modes are excited by unsteady heat release from combustion processes, such as injection, atomization, vaporization, mixing and combustion. These processes may excite acoustic modes (and vice versa) if their characteristic time is of the same order of magnitude as that of the modes, possibly leading to unstable behaviour.

The aforementioned modes can be computed through acoustic theory. The three-dimensional acoustic wave propagation in a cylindrical cavity (such as a rocket combustion chamber) can be described using continuity, momentum and speed-of-sound equations for a isentropic flow, considering very small pressure disturbances. This mathematical formulation leads to the linear equation for the propagation of a small pressure disturbance in a stationary gas, as derived by Zucrow and Hoffman (1977):

$$\frac{\partial^2 p}{\partial t^2} = a_\infty^2 \left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} \right) = a_\infty^2 \nabla^2 p \quad (9)$$

Where a_∞ is the local speed of sound. Due to this linearity, the pressure field can be obtained through the superposition of different waves that may be propagating in the three-dimensional space. Therefore, the next logical step is to characterize the shapes and frequencies of these individual waves, through a modal analysis.

By means of the method of separation of variables, and by imposing the relevant boundary conditions, one can solve the above equation for the frequencies of the acoustic modes, which can be computed using Equation (10):

$$f_{m,n,q} = \frac{a_\infty}{2} \left[\left(\frac{\alpha_{mn}}{R} \right)^2 + \left(\frac{q}{L} \right)^2 \right]^{1/2} \quad (10)$$

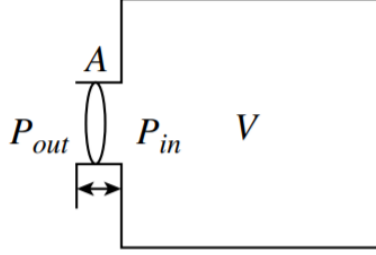
Where m , n and q are denoted as wave numbers (zero or integers), and α_{mn} is the root of the derivative with respect to the radial direction of the Bessel function of the first kind. R and L are the radius and length of the combustion chamber, respectively.

The first spinning tangential mode is proven, historically, to be most harmful inside the combustion chamber of a liquid rocket engine. The hazard is due to increased heat transfer to the walls of the chamber, caused by combustion products travelling unrestrained around its circumference, as noted by Bennewitz and Frederick (2013). Therefore, it was chosen as the acoustic mode to suppress inside the combustion chamber of the herein developed liquid rocket engine.

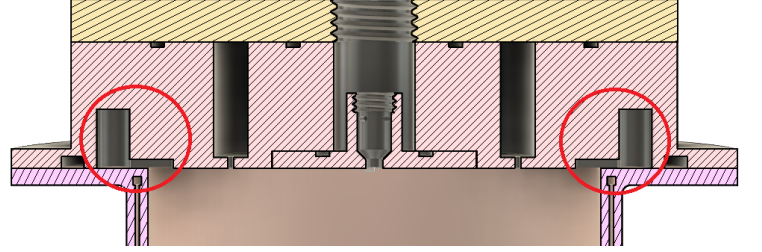
The combustion chamber diameter D_c was set to 106 mm, after imposing a contraction ratio (combustion chamber cross-sectional area over nozzle throat area) of 6. The speed of sound at the combustion chamber was found to be equal to 1087 m/s. For the first spinning tangential mode, $m = q = 0$ and $n = 1$, which yielded a frequency of 6 009.3 Hz.

In order to dampen the first spinning tangential mode, acoustic cavities were chosen over baffles as a passive control device, given their behaviour is currently better understood. The design consists in ten acoustic cavities uniformly dis-

tributed around the entire periphery of the combustion chamber, with two of them exhibiting resonant frequencies equal to the one computed above, two having resonant frequencies 5% higher, two having resonant frequencies 5% lower, two having resonant frequencies 10% higher and the last ones having resonant frequencies 10% lower than the nominal one. The ten cavities can be seen in Figure 1b. This approach aims at dampening the mode even if its frequency reveals itself to be slightly off from the theoretical one, which is expected to happen.



(a) Model of a resonator. The neck and cavity portions are easily distinguishable. Source: Kim (2010)



(b) Cross-section view of the injector assembled to the combustion chamber. A pair of acoustic cavities is highlighted.

Figure 6: Acoustic cavity model and acoustic cavity designed for the NOELLE engine

The acoustic cavities can be modeled as Helmholtz resonators, and their frequency (in Hertz) is computed as seen on Kim (2010) by the following equation:

$$f_n = \frac{a_\infty}{2\pi} \sqrt{\frac{A}{l'V}} \quad (11)$$

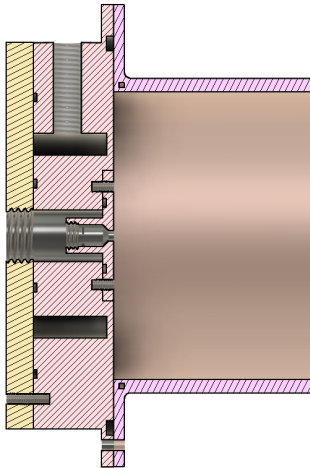
Where A is the area of the neck, l' is the effective length of the neck and V is the volume of the resonator chamber.

7. ASSEMBLY AND TEST STAND

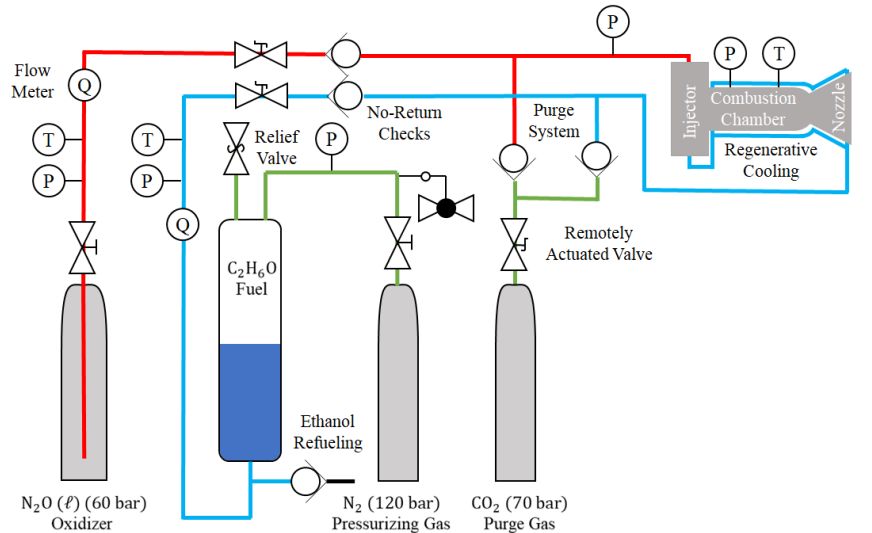
A conceptual design for the injector assembly is proposed, with ethanol being fed to the injector through the axial port, while nitrous oxide is fed through the lateral one. It is shown on Figure (7a).

Moreover, as the future goal of the present work is to conduct a hot-firing test of the designed liquid rocket engine, significant effort has been made to appropriately plan the experiment. A blueprint for the necessary safety systems and instrumentation have thus been developed.

Combining the components of the test bench, together with the safety systems and the instrumentation, a first diagram of the experiment can be formed. It is shown in Figure (7b).



(a) Cross-section view of the injector assembled to the combustion chamber



(b) Piping and instrumentation diagram of hot-firing experiment.

Figure 7: Cross section view of the injector assembly and diagram of the static fire test

Overall, this first draft of the experiment diagram already contains important details of what the test bench will become. Most importantly, it helps answer questions such as how the experiment will be controlled and performed. Furthermore, it also raises key points that still need to be determined, such as the infrastructure to hold and fix each system and the necessary exhaust evacuation lines.

8. CONCLUSION

The main performance parameters of a small-scale rocket engine with ethanol and nitrous oxide as propellants were computed. From these specifications, an analytical analysis was carried out to design both the pressure-swirl ethanol injector and the nitrous oxide plate orifice injector.

For the ethanol injector, results from numerical simulations were confronted with the outputs from the analytical results. The Volume-of-Fluid method showed good agreement with respect to discharge coefficient and film thickness at the exit, while the spray cone half-angle was considerably lower than expected due to viscosity.

Three new mechanisms for ethanol-nitrous oxide combustion were created and confronted against each other, on the basis of ignition delay. Although they showed similar behaviour, the *Marinov + Mevel* model was chosen for the one-dimensional reactor simulation, which allowed to calculate the lifetime of ethanol droplets and the combustion chamber length.

Furthermore, combustion instability was studied, with the frequency for the first spinning tangential acoustic mode (considered to be the most harmful for liquid engine operation) being computed, and acoustic cavities being designed as passive control devices to suppress this mode.

Moreover, a preliminary diagram of the test bench for the rocket engine was developed, along with the conceptual design of the injector assembly.

Future work will be focused on improving the numerical simulations for the ethanol and on carrying out cold flow tests (for both of the injectors) and a static fire test.

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10. RESPONSIBILITY NOTICE

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PROJETO DE INJETOR E CÂMARA DE COMBUSTÃO PARA UM MOTOR DE FOGUETE LÍQUIDO À BASE DE ETANOL E ÓXIDO NITROSO

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Resumo. O projeto básico de um injetor e de uma câmara de combustão de motor de foguete para óxido nitroso saturado e etanol líquido é apresentado. De início, realiza-se a seleção de uma mistura oxidante-combustível baseada em uma análise termoquímica que explora diversas opções já existentes e outras combinações ainda pouco estudadas. Como resultado, opta-se por óxido nitroso como oxidante e etanol como combustível. Então uma metodologia simplificada é proposta para o projeto de um injetor do tipo pressure-swirl para o etanol. Dinâmica de fluídos computacional é utilizada para verificar a validade da análise supracitada, empregando o método Volume of Fluid (VOF). Para o injetor de óxido nitroso, o fenômeno de flash-boiling é investigado, verificando-se sua importância para o projeto. O efeito é tratado analiticamente pelo modelo de Dyer para levar em conta a termodinâmica fora do equilíbrio. Modelos de combustão zero-dimensional e unidimensional são utilizados como ferramentas para o projeto da câmara de combustão do motor. Ainda é apresentado e discutido o fenômeno de instabilidade de combustão em câmaras de combustão de motores de foguete líquido, com o primeiro modo tangencial de oscilação acústico sendo calculado para o motor desenvolvido e um conjunto de cavidades acústicas sendo proposto para amortecer tal modo. Por fim, apresenta-se também um esquema preliminar da bancada de ensaio estático a ser utilizada para testar os injetores e o motor projetado.

Palavras chave: Motor líquido de foguete, Injetor, Combustão, Instabilidade, Cavidade acústica.