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Cold-Flow Testing of Various Injector Designs for a Novel Hypergolic and Green Propellant Combination Developed at DLR Lampoldshausen

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Abstract

In the field of space propulsion, the Green Propellants topic is a renowned recurrent trend. Between the many options available, a combination recently developed at DLR Lampoldshausen appears particularly promising, possessing most of the correct features to lead the switch to greener compounds: storability, reduced toxicity, good performance and especially hypergolicity. The propellant combination is an ionic liquid fuel, coupled with highly concentrated hydrogen peroxide as oxidizer, the so-called HIP_11. The present study describes various injection approaches, describing the multifaceted challenges encountered. The study is completed by a cold-flow test campaign that investigated the spray pattern of the various designs.

1. Green Propellants and the Hypergolic Combinations

Hypergolic propellants have long been the preferred choice for the overall propulsion system of medium and large spacecrafts and upper stages, having been employed indiscriminately for both Main Engines and Attitude Control Systems for in-space applications. The versatility comes from their inherent ignition capability upon contact, which allows for reliable and instantaneous combustion. The utilization of hydrazine or its derivatives as the fuel and dinitrogen tetroxide (NTO) as the oxidizer has a heritage that goes back to the very beginning of space exploration with applications spanning from lunar module landings to deep space missions.
Unfortunately, hydrazine and its derivatives, namely unsymmetrical dimethyl hydrazine (UDMH) and monomethyl hydrazine (MMH), are known to be toxic and carcinogenic substances and in Europe, hydrazine has been listed as a substance of very high concern under the REACH regulation, which may lead to its potential ban, regardless their current crucial role for present lunar missions, as exemplified by the European service module of the Orion spacecraft. The adverse properties of traditional hypergolic propellants necessitate extensive safety precautions during their handling and ground operations, including the use of self-contained atmospheric protective ensembles (SCAPE) suits. Consequently, the production, storage, transportation, and fuelling processes of these propellants incur substantial additional costs.
The development of alternative green propellants aims to overcome the challenges associated with the dangerous and highly toxic nature of conventional propellants. By utilizing green propellants, it is possible to potentially reduce the extent of safety handling requirements, offering significant cost-saving opportunities. Many green alternatives exist, developed by numerous industries and research centres around the world, although only a few have reached a maturity level high enough to be considered widely available, with a growing difficulty into selecting the most adequate for different scenarios [1]. The maturation of the most promising alternatives is a crucial step to make them really appealing for the overall space market.

1.1 HIP_11

The department of Satellite and Orbital Propulsion at DLR's Institute of Space Propulsion in Lampoldshausen has a long heritage of research activities focused on the development and testing of environmentally friendly propellants for

DOI: 10.13009/EUCASS2023-379

space applications. Within the advanced rocket propellants group, one of the main objectives of the last few years has been to develop novel hypergolic green propellants. This development process includes several stages, ultimately aiming at testing the new green hypergolic alternatives in a demonstrator to establish its performance parameters.
Initially, the utilization of highly concentrated hydrogen peroxide as the oxidizer was chosen due to its suitability as a green and storable oxidizer. Concurrently, the liquid fuel development has been centred around new hypergolic ionic liquids, which offer the advantage of having an exceptionally low vapor pressure under ambient conditions, thanks to their unique ionic structure. A preliminary screening of various ionic liquids was conducted, and many alternatives were investigated in drop tests [2]. A particularly promising propellant showed good properties in terms of performances, stability, and suitability as rocket fuel. The propellant, hereby referred to a HIP_11, is an ionic liquid based on thiocyanate (EMIM SCN) that contains a variable quantity of dissolved copper thiocyanate (Cu SCN) in order to quickly react with hydrogen peroxide.
The handling of the compound does not necessitate the use of specific protective equipment such as a SCAPE suit, and its physical characteristics do not require specialized procedures. The only distinctive attribute of the propellant is its dynamic viscosity, which is noticeably higher than that of conventional propellants. It has a dynamic viscosity of 29.55 mPa s, element that poses challenges to the operations of the injectors, as described below.
The propellant combination HIP_11 (ionic liquid fuel and high grade H_2O_2, HTP, as oxidizer) is under investigation by some years, and it has undergone multiple research steps, from droplet and ignition characteristics studies to hot-firing tests in prototype combustion chambers [3, 2]. The initial drop tests, conducted to assess various alternative propellants, demonstrated an ignition delay of approximately 30 ms of the pure ionic liquid. The addition of a copper promoter reduces the ignition delay time to 12 ms, a value comparable to existing and commonly used hypergolic combinations. Subsequent drop tests performed in controlled environments further validated these findings and explored the influence of factors such as propellant quantities, drop height, and fuel-to-oxidizer ratio.

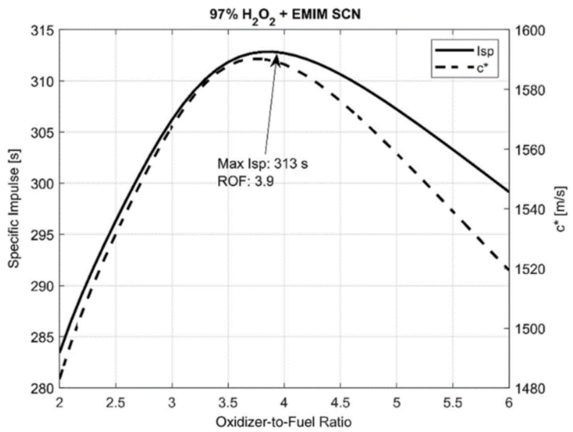

Figure 1 - Theoretical performances of the green propellant combination. Theoretical performances obtained with NASA CEA. Courtesy of [4].

Building upon the success of the drop tests, the propellant combination underwent testing in a prototype combustion chamber for ignition and hot-fire experiments. The ignition tests specifically examined the use of an impinging injector configuration (2-on-1) to facilitate the mixing of the two compounds and subsequent ignition [3]. The tests outlined positive results, with the prototype thruster being successfully ignited multiple times, displaying stable behaviour and combustion pressure oscillations below 2%.

1.2 Prototype thruster

The existent modulable prototype thruster has been developed to test and expand the understanding of the propellant combination suitability as green alternatives. It has already undergone a comprehensive series of tests to validate its performance and functionalities, demonstrating the reliable ignition of the propellants under various conditions utilizing a 2-on-1 oxidizer to fuel triplet injector [4, 3]. The primary objective of the prototype development is to evaluate the propellant combination's suitability for generic applications, but with a particular focus to small-thrust-class engines, specifically targeting a thrust range in the order of 50N in vacuum conditions.
The prototype aims to provide insights into the performance characteristics, efficiency, and feasibility of the proposed propellant combination for such applications, but also for bigger-size and diverse employment. The outcomes of the research have the potential to advance the field of green propulsion by offering valuable knowledge for the design and optimization of small-scale thrusters based on the novel and promising combination.
The reasons to focus on small-size thruster applications can be categorized as:

DOI: 10.13009/EUCASS2023-379

- <u>Safety reasons</u>: Despite comprehensive studies and thorough characterization of the propellants, the ongoing prototype development is still in its preliminary stages. It is important to note that due to the inherent properties of these compounds, dealing with large quantities necessitates the utmost caution and adherence to delicate procedures.
- <u>Market reasons</u>: The selected engine size is probably the most utilized in the field of space propulsion. A 50N thruster is the best fit for Attitude and Reaction Control Systems for satellites and small stages. Furthermore, it serves as a viable option for being employed as the Main Engine in small satellites, facilitating relatively small manoeuvring operations. The decision to apply the propellant combination to this specific engine class is, hence, a direct derivation of market demands, although it presents notable technical challenges that must be addressed.

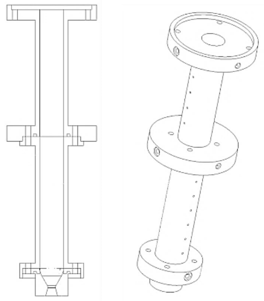

Figure 2 - Modulable Prototype, base of the study.

To obtain a thrust of around 50N in vacuum with a properly expanded nozzle, the thrust level is set to around 25N at ambient condition without an expanded nozzle.
Knowing the thrust level and the optimal Oxidizer to Fuel Ratio (O/F) of the propellant combination, it is possible deriving the remaining design input conditions, summarized in Table 1.

Table 1 - Prototype Characteristics and Derived Injectors Requirements

Engine Prototype - Design Characteristics		
Thrust	25N @ ambient conditions, truncated nozzle	
Combustion Chamber Pressure	10 bar	
Propellants ideal O/F	Around 4	
Total Mass Flow Rate	12 g/s	
Injectors Requirements		
	Fuel	*Oxidizer*
Compound	HIP_11 - 100% EMIM SCN	98% Hydrogen peroxide – 2% Water
Mass Flow Rate	2.4 g/s	9.6 g/s
Desired Pressure Loss across Injector	8 bar	8 bar

1.3 Prototype Injector Requirements

From the thruster prototype description, it is possible extracting the injectors requirements.
The design pressure in the combustion chamber pressure is set to 10 bar, a typical value for thrusters of this size based on liquid hypergolic propellants. The pressure drop across the injectors is fixed at a conservative value of 8 bar for both propellant components. The value may appear elevate, but it was selected in order to protect the lines from eventual unpredicted pressure spikes in the combustion chamber while also using a plausible value of feeding pressure, commonly found in other equivalent thrusters.
The greatest challenge encountered in the development of the injectors for the prototype is doubtlessly achieving the required low mass flow rates. These flow rates are on the order of a few grams per second, necessitating the design of extremely small orifices that present limitations in terms of manufacturing capabilities and physical constraints. Moreover, the physical properties of the propellant further extend the challenge. The injector designs must address the need for physical separation between the propellant for safety reasons, as well as account for the high viscosity of the fuel, which poses difficulties in effectively filling the lines and cavities during the transients.

To summarize, the ongoing development of the prototype necessitates the careful design of the injectors to ensure the successful achievement of:

- A pressure drop across the injectors of around 8 bar for both propellants,

DOI: 10.13009/EUCASS2023-379

- A reliable operation with the reference fluids,
- A reliable and repeatable spray pattern,
- An enhanced atomization and mixing processes of the two propellants inside the combustion chamber,
- A safe delivery of propellants inside the combustion chamber

2. Proposed New Injector Designs

The functions of the injectors in chemical liquid thrusters for space applications are straightforward but nonetheless critical for the correct operation of the system. The component is, without any doubt, one of the most important drivers of a stable combustion and correct operation of an engine.
The primary function of the injectors is to introduce and control the different flows of liquid compounds in the combustion chamber, however there are many physical phenomena happening almost simultaneously that are directly impacted by the design, such as fluid atomization, vaporization, and reaction.
In the case under analysis, where the propellant is liquid and hypergolic, the injector design is crucial for the correct promotion of a smooth ignition and combustion by controlling and boosting the correct mixing of the propellant in the chamber. The mixing process of two liquids , especially if hypergolic, is a delicate physical phenomenon that consists into two distinct stages: atomization and mixing. The former consists into breaking the fluid stream into small droplets, distributing it into a relatively big volume, while the latter is the process where droplets of different fluids combine in order to react and start combustion [5].
The methods utilized to fulfil these functions are multiple and allow to generate many different designs, each one presenting strengths and weaknesses depending on the application. Generally speaking, injector designs can be divided into two broad categories: impinging and non-impinging [6]. As the definition suggests, the first case is based on two or more streams striking between each other in order to break the flow and atomize it. The second family consists of a multitude of other methods to break the flow, such as using pressure or internal physical barriers that direct the flow.
Impinging injectors are, usually, easier designs that are able to work in a multitude of different operating conditions. Their mixing performances are very variable, and the resulting spray is often not well distributed as required. Non-impinging injectors are many and very different between each other. Between the non-impinging injectors, the most common design for space and non-space applications is probably the so-called swirl injector, that uses a tangential acceleration of the fluid to create a swirling motion that, once ejected, atomizes distributing the resulting droplets very efficiently.

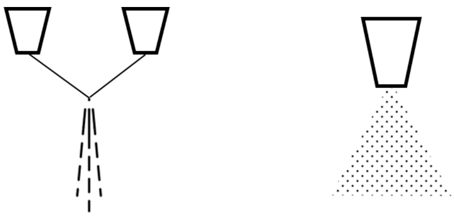

Figure 3 - Impinging injectors on the left use two or more streams impinging between each other to atomize the fluid. Example of non-impinging injector on the right that does not need streams impinging to atomize the fluid.

In general, the design of an injector necessitates careful consideration of the pressure loss experienced by the fluid as it traverses through the injector. The hydraulic relationship governing the flow within an injector, which establishes a connection between mass flow rate and pressure loss, can be derived from the Bernoulli equation applicable to an incompressible medium.

$$\dot{m} = C_d A \sqrt{2 \rho \Delta P} \qquad \textit{Equation 1}$$

Where ρ is the fluid density, ΔP the pressure loss along the injector, A the equivalent area and C_d the so-called discharge coefficient, a dimensionless parameter that quantifies the efficiency of fluid flow through the injector, usually quantified as the difference between an ideal and a real fluid through an injector.

$$C_d = \frac{\dot{m}_{real}}{\dot{m}_{ideal}} \qquad \textit{Equation 2}$$

The parameter assumes a value between 0 and 1, since real mass flow rate is always smaller than the ideal value that conventionally does not consider friction, viscosity, and pressure differentials.
There exist several methodologies for estimating the discharge coefficient (C_d) for different injector designs; nevertheless, the final evaluation necessitates experimental verification due to its high sensitivity to manufacturing

DOI: 10.13009/EUCASS2023-379

variabilities and other unpredictable effects. Typically, experiments employing water or harmless fluid simulants are conducted to characterize the injectors before undertaking actual tests and operations.
The primary purpose of the injector is to introduce a predetermined mass flow rate into the combustion chamber. Equally significant is the consideration of fluid velocity and properties during the injection process, as well as the surface tension of the fluid. To study these parameters, it is common utilizing dimensionless numbers. In particular, the mass flow rate, fluid viscosity μ, and velocity U are connected through the utilization of the Reynolds number, which provides a valuable characterization of the fluid flow dynamics and helps assess the potential for turbulent or laminar flow within the injector:

$$Re = \frac{\rho U D}{\mu} = \frac{4\dot{m}}{\pi D \mu} \qquad \textit{Equation 3}$$

Turbulence can promote a better atomization by introducing instabilities in the flow that tend to break up the liquid into smaller droplets. The discharge coefficient strongly depends on the turbulence regime, becoming constant at high values of Reynolds number as shown in Figure 4, hence the injection velocity is commonly designed accordingly.

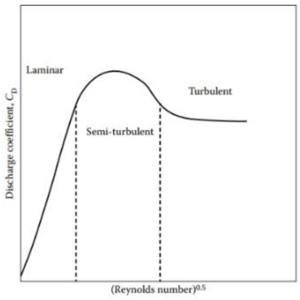

Figure 4 - Discharge Coefficient and Reynolds number – Courtesy of [5]

This aspect becomes particularly delicate when dealing with fluids possessing high viscosity, such as the fuel under examination, as elevated viscosity values (μ) diminish the Reynolds number, thereby favouring laminar flow rather than the desired turbulent regime.
The other characteristic dimensionless parameter usually analysed is the Weber number, that relates the the fluid surface tension, σ, with inertial forces in the fluid:

$$We = \frac{\rho U^2 D}{\sigma} = \frac{16}{\pi^2}\frac{\dot{m}^2}{\rho D^2 \sigma} \qquad \textit{Equation 4}$$

The Weber number expresses the ratio between inertial forces trying to disperse the phases during the atomization, to the interfacial forces trying to keep them distinct. It is usually used directly on droplets, and used in orifices is a broad simplification. The higher the Weber number, the larger is the impact of inertial forces compared with the surface tension forces, and the fluid will tend to break in smaller droplets [5].
In general, viscosity can in be considered the most important liquid property for a correct atomization. While surface tension plays a crucial role, viscosity's significance lies in its impact on various aspects, including drop size distributions, nozzle flow rate, and spray pattern. The increase in viscosity results in a reduction in the Reynolds number that naturally goes against the development of natural instabilities in the jet or sheet, delaying the formation of a well-atomized spray pattern.

Previous tests on HIP_11 explored the utilization of impinging injectors for the combination of propellants analysed [4]. Previous experiments explored the utilization of an unlike triplet design, with a single 2-on-1 injector composed by a central fuel orifice and two outer oxidizer orifices, with a design schematic similar to the one shown in Figure 5. The component is without doubts one of the easiest solutions, widely described in literature. Nonetheless the design had to overcome many challenges, mainly connected to the very low mass flow rates and manufacturing capabilities.

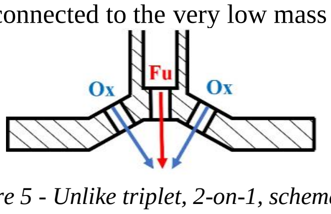

Figure 5 - Unlike triplet, 2-on-1, schematics

Results from cold-flow and hot firing tests of the injector design were promising, the solution showed a good response along the test campaign [3]. The design, however, possessed a clear and inherent non-symmetry that raised concerns

DOI: 10.13009/EUCASS2023-379

during the prototype development. Additional designs were hence proposed and developed in order to improve the existent prototype and increase mixing efficiency and droplets distribution.
The original impinging 2-on-1 triplet design, which spray pattern is shown in Figure 6, has been used as baseline for the comparison of new proposed alternatives.

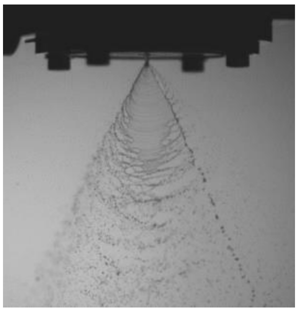

Figure 6 - Spray pattern of the 2-on-1 injector, frontal perspective. Feeding pressure of 7 bar in both lines.

New designs explored 3 improvement areas:
- Impinging Injectors with higher number of streams impinging;
- Swirl Injectors:
  - Commercial Single Swirl Injectors;
  - Double Coaxial Swirl Injectors;
- Impinging-Swirl Hybrid Injectors.

Based on the aforementioned principles, several designs were proposed and studied more in detail. The main purposes of the new designs were:
- Improve the spray distribution, making the atomization uniform and symmetrical inside the chamber;
- Make an attempt at utilizing a stream of oxidizer/fuel to cool down the combustion chamber (film cooling);
- Make the mixing characteristics of the propellants as quick and uniform as possible.

After a Preliminary Design Review, some designs were proposed, fabricated and tested in a dedicated test bench to better understand the output spray pattern and behavioural ejection characteristics. It follows a description of the new designs proposed for the prototype.

2.1.1 4-on-1 Impinging Injector Design

As mentioned, impinging injectors are relatively very easy and commonly and historically used with storable propellants in space and non-space applications [7]. Historical examples of their use are aligned with the project goal, being commonly used in small and medium rocket engines.
The 4-on-1 impinging design derives from a direct improvement of the 2-on-1 design, that proved to be valid. The unlike triplet is inherently non-symmetrical, and the 4-on-1 is a direct tentative of improving the situation. Moreover, literature describes how an increased number of orifices should improve the mixing ratio of the propellants [7, 8].
The design is based on 4 streams of oxidizer impinging on a single flow of fuel. With an analogous reasoning to the 2-on-1 design, the optimal oxidizer to fuel ratio is high, and hence the mass flow rate of oxidizer is larger in magnitude. It is natural designing the single orifice for the fuel in the centre that impinges four streams of oxidizer from dedicated orifices equally disposed circumferentially (Figure 7).
The main challenge of the design is without doubts the manufacturing of the component. Being the size of the prototype very small, the necessary orifices diameter is exceedingly small. The dedicated feeding lines proved to be likewise challenging. Being the propellants extremely reactant when in contact, for security reasons the feeding lines should remain as physically separated as possible, with multiple security mitigation in place to avoid spillages or inadvertent decomposition. Tests of the design are furtherly described below.

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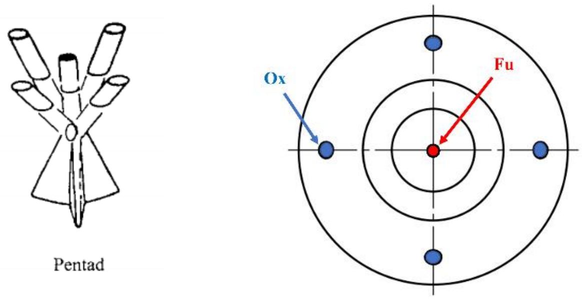

Figure 7 – Schematics of the spray pattern [7] and bottom view of the 4-on-1 injector design.

2.1.2 Swirl Injectors Design

Swirl injectors are a type of non-impinging injectors, they atomize the fluid by introducing a swirling motion in the fluid. The components have an extensive use heritage in the space sector, having many examples of thrusters based on them. The introduced swirling motion in the fluid creates a conical spray pattern that enhances atomization, leading to improved combustion efficiency and stability.
Its main advantages respect to the more classical impinging designs are that they tend to distribute more uniformly the propellants in the chamber and consequently produce reduced combustion instabilities and enhanced overall performances. However, the design presents also some disadvantages connected to their mechanical design and manufacturing complexity and increased sensitivity to injector clogging [7, 5]. A generic schematic of the two main types of swirl injectors is reported in Figure 8.

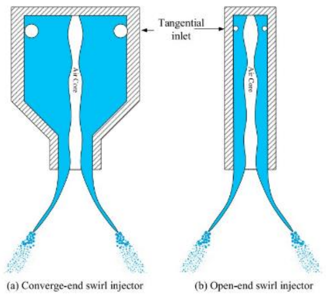

Figure 8 - Swirl Injector schematics. Courtesy of [9]

Swirl injectors are well-known and well-reported to be particularly efficient for delivering a substantial mass flow rate into the combustion chamber while continuously featuring good propellant atomization and distribution. The design procedures extesively described in literature [10, 7] and used for the design are mostly based on applications featuring low-viscosity fluids such as kerosene and mass flow rates of many dozens of grams per second. The application under analysis requires extremely low mass flow rates, in the order of under 3 g/s for the fuel and less than 10 g/s for the oxidizer. In addition, while the oxidizer is a low-viscosity fluid, similar to water, the fuel presents a modestly high value of dynamic viscosity, more than an order of magnitude bigger. It was, hence, expected a deviation of the real behaviour from the theoretical design.
Two options have been explored for the swirl injectors: commercial single swirl injectors and double coaxial swirl design. The former is an option explored to study the behaviour of available components off-the-shelf under the operating conditions of low mass flow rate and high viscosity, creating a baseline, while the latter is the desired operating component, supposed to be part of the engineering model.

Double Swirl Coaxial Injector

The design of double coaxial injectors is extensively utilized for space thrusters and hypergolic propellants [11, 12]. The schematics of the spray pattern and injector design are shown in Figure 9. The operating principle is based on two independent conical spray patterns that evolve almost in parallel.
The two sprays can be designed to impact or not, with different cascading effects. The peculiarity is that the external cone can be designed to impact first with the combustion chamber wall, contributing to the material temperature management (film cooling). The latter feature is the main characteristic that made the design promising for the prototype under analysis.

DOI: 10.13009/EUCASS2023-379

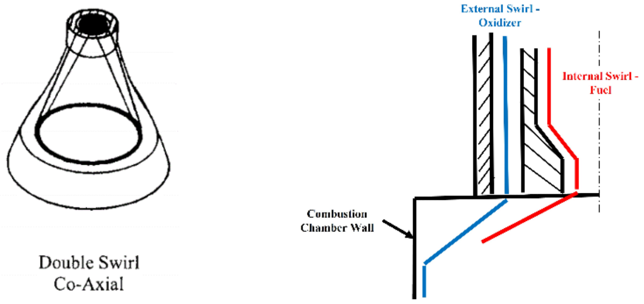

Figure 9 - Schematics of the spray pattern, courtesy of [7], and injector design

The external spray cone was set to oxidizer and the internal to fuel:

- The oxidizer mass flow rate is bigger, and being a concentric injector the external physically results into bigger orifices.
- The lower dynamic viscosity of the oxidizer made it more suitable for creating a uniform and spread spray pattern.
- The theoretical cooling characteristics of hydrogen peroxide make it the best choice for film cooling.

The design choice, however, came with dedicated challenges, especially connected to the interaction between the two spray cones, possible quick decomposition of hydrogen peroxide and reliable operations of swirl injectors with low mass flow rate and viscous fluids as in the case of the fuel.
The latter mentioned concern assumes particular significance, given the high viscosity of the fluid and the fixed mass flow rate, resulting in an exceedingly low Reynolds number, as depicted in Equation 3. Consequently, the possibility of laminar flow raises doubts regarding the establishment of a consistent and well-atomized spray cone pattern.

Commercial Injectors

Additional to the customized designs, the utilization of commercially available components was explored to verify the behaviour of the propellants under various conditions. Swirl injectors have been extensively studied applied in many fields, very often for applications extremely distant from space thrusters such as agriculture or industrial plants. Most of the designs do not follow the theoretical characterization described by many authors in literature and applied in the internal designs, but instead utilize different strategies to create the swirling motion inside the injector.
Most of the off-the-shelf components rely on additional utilize internal elements within the injector assembly, which are strategically positioned along the flow path to induce a swirling motion and facilitate the formation of the desired spray cone.
These components are hereby referred to as “inserts” and are the foundation of extremely reliable injectors that are used in multiple applications. There are dozens of commercially available components for different operating conditions, including designs for limited mass flow rates and high viscosity fluids.

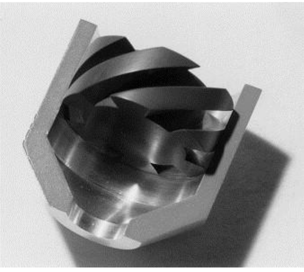

Figure 10 - Example of insert design for a swirl injector. Image courtesy of [13]

Despite a widespread application of the inserts in many designs, the information about them is limited in literature, that usually is limited to the study of theoretical flows. Numerous supply companies have conducted peer-reviewed investigations on their products; nevertheless, the design selections are commonly treated as confidential information, and it is probable that these designs were developed internally using proprietary methodologies, without divulging the explicit rationale behind the design choices.
Different components were procured to be tested at different operating conditions (feeding pressure, fluid and related mass flow rate) although designed for application far from rocket science. Nonetheless, the performances advertised by the supply company were compatible with researched characteristics.

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2.1.3 Swirl – Impinging Hybrid Design

The final proposed design consists in a hybrid configuration combining features from both swirl injectors and impinging designs. The rationale behind this design approach is to harness the benefits offered by each option while addressing the challenges inherent to both alternatives. By merging key aspects, the proposed alternative is aimed to achieve a design that optimally balances performance and mitigates potential limitations, especially those connected to fluid instabilities and manufacturing.
In particular, the design made an attempt at utilizing the swirl injector's spray pattern to establish a protective oxidizer film on the combustion chamber wall, intended for cooling purposes Simultaneously, the design incorporated the simpler impinging concept for the fuel injector part, employing three streams to impinge upon the spray cone, facilitating the atomization and mixing of the two propellants.

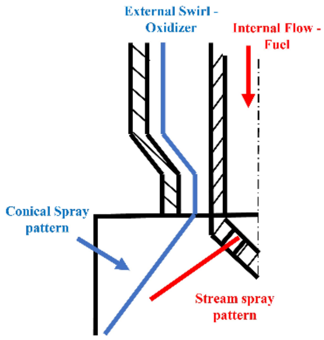

Figure 11 - Schematics of the Swirl – Impinging Hybrid Design

While the description of the design is of more difficult comprehension, the operation should be easier. The oxidizer spray pattern is a hollow cone that impinge the combustion chamber wall around all the circumference, creating a film of propellant that is supposed to protect the wall from the extreme combustion temperatures. The fuel spray pattern is three streams of propellant ejected radially from the intern of the hollow cone. These three streams impinge on the conical spray pattern, atomizing and mixing the propellants as intended.

3. Injector Designs Testing

Injectors are complex components that play a crucial role in the correct operations of engines and overall propulsion systems. The intricate nature of injectors involves multi-physics, coupled, phenomena that are impossible to capture and predict during the design phase. The components are sensitive to various operating parameters as well as to manufacturing variabilities, and their direct impact on combustion efficiency and engine performance necessitate comprehensive testing to ensure optimal functionality and reliability.
Through dedicated testing, it is possible identifying potential issues, validate design choices, optimize performance, and ensure compliance with stringent requirements. The tests performed on the proposed designs aimed at validating the design choices by varying operating conditions, fluid properties, and potential interactions with other components. The output that the test campaign aimed to achieve are:

- Spray pattern validation and visualization under various operating conditions (feeding pressure and fluid properties).
- Verification of the injector operations for the designed mass flow rate and pressure loss.

The following sections describe the test bench that has been used for the performed cold-flow testing campaign and the obtained results in terms of spray pattern and other characteristics.

3.1 Test Bench Description

The injector designs have been tested in a dedicated cold-flow testbench at M11.5 in DLR Lampoldshausen, specifically designed for injector evaluation, aligning with the objectives of the study. However, the testbench was not certified for compatibility with the actual propellants employed and consequently simulant fluids were utilized to replicate the necessary characteristics. Additionally, visualizing the spray behaviour of hypergolic propellant combinations is easier with simulants than with the propellants itself due to instant combustion after contact.
The testbench is composed of a high-pressure nitrogen line to pressurize the system, but each fluid possesses an independent line, allowing for distinct feeding pressures by PID-controlled pressure regulators. The testbench

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facilitated both individual and simultaneous testing of the injectors, enabling the evaluation of a single injector at a time (i.e. only-fuel or only-oxidizer injection), as well as the examination of their combined operations.
Mass flow rate, pressure and temperature are measured in both lines upstream the injection. In this way it is possible estimating the injector pressure loss and the discharge coefficient knowing the ambient static pressure and using Equation 1 and 2. For measurement data acquisition, a real time measurement system was used for high frequency measurement.

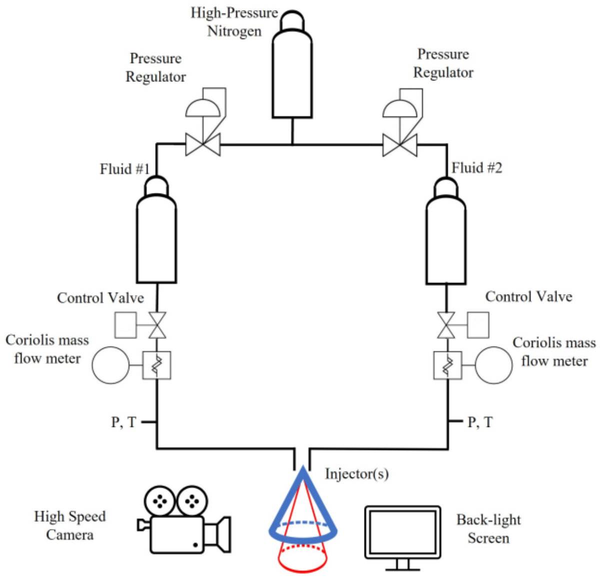

Figure 12 – Cold-flow testbench - Simplified Schematics

The injectors were assembled in their respective injector heads, excluding the presence of the combustion chamber to visualize the spray pattern. A shadowgraph setup with a high-speed camera and backlight was employed to capture images and short videos, enabling a high-quality visualization of the spray pattern produced by the injectors. This visualization is crucial for estimating the atomization and mixing of propellants within the combustion chamber. In addition, the shadowgraph images are synchronized with the data acquisition, hence the captured footage can be linked to the data analysis. One injection test was performed until the transient start-up phase run through and a steady pressure drop and mass flux could be observed.
Although the fluids were injected into an ambient pressure environment, it is postulated that the observed effects will be similar when translated to higher pressure conditions. Difference can be significant, although atomization is commonly faster at higher ambient pressures. It is important to acknowledge that various conditions within the combustion chamber can have a profound impact on the breakup length and atomization process, regardless of the ambient pressure, and all these effects are neglected in the current study for the impossibility to quantify them.
While droplet size measurements were not conducted, the obtained visual data provides valuable insights into the distribution of the atomized flows.

3.2 Experiments Description

In total, over 50 injection tests were performed, studying the different injector designs at different operating conditions. Only some selected results are shown in this study to describe the conclusions.
The injector designs underwent the cold-flow testing campaign to assess their suitability and characterize their features. Specifically, the following key aspects were investigated:

- Spray pattern at the design operating conditions (feed pressure and mass flow rate as described in Section 1.3), using various simulant fluids;
- Spray pattern at operating conditions different from the design, with various simulant fluids;
- Discharge coefficient of the various designs.

The outputs have been obtained by varying a limited number of parameters at a time. Specifically, the following parameters were selectively modified:

- Feeding pressure was varied starting from 2 bar up to 20 bars.
- Simulant fluid.

DOI: 10.13009/EUCASS2023-379

Table 2 summarizes the simulant fluid properties compared to the original characteristics. In particular, the simulant fluids tried to reproduce the features of the original compounds deemed more important for the injection process, while remaining safe to manage and easy to procure.

- Water to simulate hydrogen peroxide. It is recognized that a correction factor is needed to reproduce the density difference, that will cause an increase of peroxide mass flow rate at equivalent conditions.
- A mix of glycerine and water (70%-30% glycerine-water on the mass) to simulate fuel properties.

Table 2 - Physical characteristics of the propellants and the utilized simulant fluids

Property	98% H_2O_2	Water	HIP_11 fuel [2]	Glycerine Mix [14] (70%-30% Water)
Density (@ 20°C)	1431 kg/m^3	998.2 kg/m^3	1150 kg/m^3	1181 kg/m^3
Dynamic Viscosity (@ 20°C)	1.15 mPa s	1.00 mPa s	29.55 mPa s	23.16 mPa s
Surface Tension (@ 20°C)	80.4 mN/m	72 mN/m	47.2 mN/m	60 mN/m

Most of the fluids' physical characteristics, and especially the dynamic viscosity and surface tension, are strongly dependent on temperature. Fluids are compared considering a reference temperature of 20°C, however it is recognized that the real value was often lower.

The following parameters were measured during the tests to characterize the injection process and related components:

- Mass flow rate by using dedicated calibrated Coriolis sensors.
- Pressure and temperature upstream the injectors by using differential transducers and thermocouples.
- Spray pattern by using a dedicated high-speed shadowgraph setup.

3.3 Cold-flow Test Results

The results obtained from the test campaign are presented here, categorized according to the respective injector designs. These results include the visualization of the spray pattern under specific feeding pressures, as well as the measurement of the mass flow rate during the defined analysis window.

The tests allowed us to determine the optimal feeding pressure required to achieve the intended spray pattern, as well as the corresponding mass flow rate. Based on Equation 1 and 2, once the discharge coefficient is fully characterized, there exists a direct correlation between the mass flow rate and the pressure drop. Consequently, for a given pressure drop value, a specific mass flow rate can be determined. It is important to note that the discharge coefficient is not constant with the pressure drop if the fluid is in the laminar regime. The injectors are designed to operate in the turbulent regime, but in case the condition is not respected it is assumed, as initial approximation, that the coefficient remains constant and further tests using the finalized prototype are necessary to validate this assumption and increase the precision.

3.3.1 4-on-1 Impinging Injector Design – Test results

The quadruplet 4-on-1 design spray pattern is shown in Figure 13. The tests have been performed using water in the oxidizer injector and the glycerine-water mix as simulant fluid in the fuel injector, hence the results in terms of mass flow rate should be close to the operations with the real compounds.

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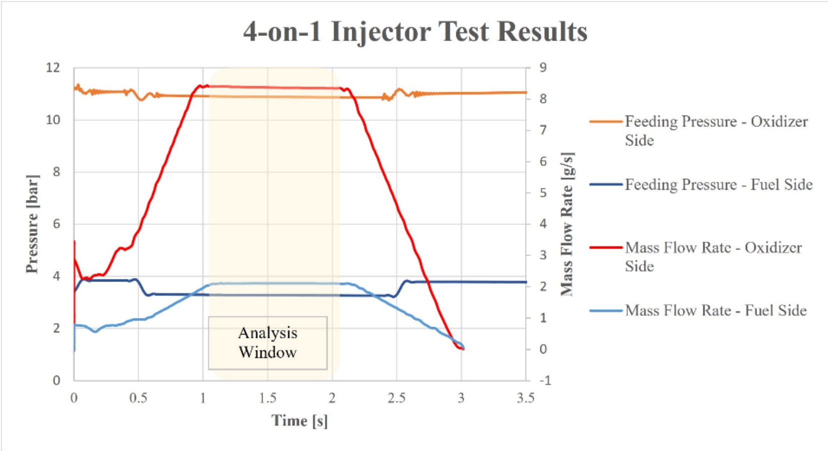

Figure 13 - Spray pattern snapshot and measured features of the impinging 4-on-1 design

The picture of the spray pattern clearly shows how the spray pattern exhibits a distinct axial momentum directed towards the outlet, with the ejected mix composed by a single stream with apparent high momentum. The observation of a single stream may suggest that the propellants are optimally mixing while potentially not atomizing effectively.
The injectors are easily tuneable to the correct mass flow rate values at feeding pressure values not too high. Particularly, the feeding pressures utilized to obtain mass flow rate values close to the design are:

- around 11 bar in the oxidizer side (mass flow rate of 8.4 g/s).
- 3.7 bar in the fuel side (mass flow rate of 1.9 g/s).

Table 3 summarizes the overall evolution of the dimensionless parameters that help drawing conclusions on the spray pattern characteristics. The steady state is calculated on the average inside the analysis window, while the transient is considered at 0.25 seconds before the analysis window. The reference dimension is the area of the equivalent outlet.

Table 3 - Dimensionless numbers for the 4-on-1 impinging injector test

	Fuel Side		**Oxidizer Side**	
	Transient	*Steady*	*Transient*	*Steady*
Re	100	210	15,600	26,700
We	0.08	0.33	0.15	0.6
C_d	0.19	0.38	0.19	0.37

From the shadowgraph images, the spray pattern exhibited a rapid development, without visible transient behaviour. The mass flow rate measurements, instead, indicate a gradual approach to steady state, not visible from the spray pattern pictures. The behaviour can be explained looking at the Reynolds and Weber numbers. The Reynolds number for the oxidizer flow indicates a turbulent regime since the first instants of operations, that drives the overall spray pattern. The low values of both Reynolds and Weber numbers for the fuel flow indicate that the flow is not atomizing properly, although the subsequent impact with the impinging oxidizer flows seems driving the spray development.
The low values of Weber numbers partially indicate the insufficient atomization. The Weber number, however, does not consider the following impinging process that strongly contributes to the final atomization of the fluids and the overall spray pattern formation.

3.3.2 Swirl Injector Designs – Test results

The various swirl injectors have been tested at various conditions. The experiments conducted on these injectors were extensive, aiming not only at testing the components, but also at studying and deepening the understanding of the working principles of the components.

Double Swirl Coaxial Injector

The tested design, as described in Section 2.1.2, consists of two separate injectors that are designed to operate independently, but collectively they are expected to exhibit a coherent spray pattern. Both individual components were tested independently, as well as in conjunction with pure water and the simulant fluid, to thoroughly assess their

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behaviour and spray pattern under various operating conditions with different fluids. Table 4 summarises the experiment configurations, tested at various conditions.

Table 4 - Design of Experiments for the coaxial swirl design

	Fuel Side	**Oxidizer Side**
Test #1	Water	\\
Test #2	Simulant Fluid	\\
Test #3	\\	Water
Test #4	Water	Water
Test #5	Simulant Fluid	Water

From the tests, it is possible obtaining valuable insights regarding the operation of the injectors and the factors that influence their performance. A significant observation can be made by comparing Test#1 and Test#2, assessing the impact of viscosity on the spray pattern and atomization of the propellants, Figure 14. By analysing these two tests, we can gather essential information about the behaviour and characteristics of the injectors under varying viscosities. As shown in Figure 14, the spray pattern of the low-viscosity fluid, water, on the left-hand side is fully developed, demonstrating good atomization properties at a feeding pressure of 10 bar. Contrarily, it is evident that the spray pattern of the high viscosity fluid is poorly atomized compared to water and it is not fully developed.

Table 5 - Dimensionless numbers during Test #1 and #2

	Fuel Side	
	Water	*Simulant*
Re	18,000	715
We	0.6	0.3
C_d	0.26	0.35

As shown by the study of dimensionless numbers (Table 5), the high viscosity of the fluid decreases the flow momentum, resulting in a lower Reynolds number, calculated using the tangential orifice of the swirl injector as reference dimension, placing the injection process into a laminar regime. The regime can change in different zones of the injector, with the variation of equivalent area and fluid velocity, however the analytical calculation of the fluid is dependent from too many factors to be calculated, hence the regime is supposed constant and equivalent to the injection orifice condition. The laminar flow is detrimental to achieving proper atomization, particularly for swirl injectors.
The Weber number calculated for swirl injectors is not ideally defined and should utilize the spray layer thickness instead of the orifice diameter as reference dimension. Unfortunately, the parameter is not measurable in the described setup. For this reason, conclusions using the Weber number are not possible for this type of injectors.

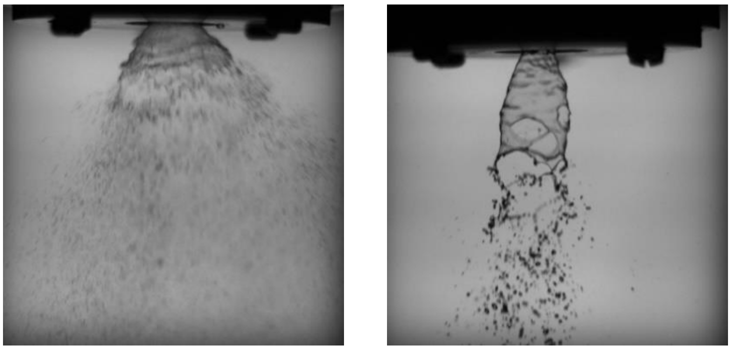

Figure 14 - Comparison between Test #1 and #2, Feeding Pressure of 10 bar. Working fluid: water in the left-hand side picture and viscous simulant fluid in the right-hand side picture

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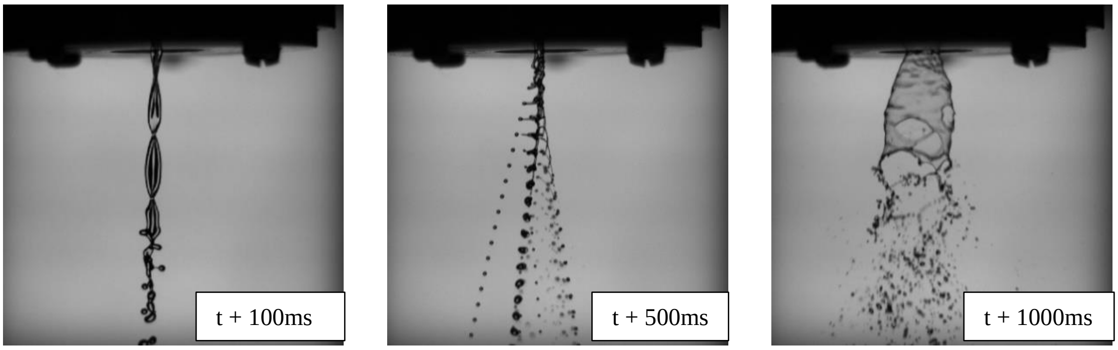

Figure 15 - Transient of the swirl injector with the viscous simulant fluid. Pictures taken at different timesteps from the opening valve. Feeding pressure of 10 bar.

Another very important outcome of Test#2 is the study of the injector transient when using viscous fluid. As shown in the sequence of Figure 15, the injector requires a substantial amount of time to develop a spray pattern as designed and required. The start of the test is determined from the moment the control valve is open and the first droplet is emitted without notable delay.
Finally, the study of mass flow rates in Test#1 and #2 showed that the obtained values were more than double the designed (water operation in Figure 14 is around 4.5 g/s, while with simulant fluid is around 5.2 g/s), at 10 bar of feeding pressure. In addition, a full spray cone never developed reliably for values below these, that hence represent the thresholds of the lowest achievable mass flow rates by the injector.

Test#3 explored the oxidizer side injector (external swirl), showing good behaviour and response of the system, with a reliable spray pattern. From Figure 16 it is clear how the spray pattern is well atomized, and the cone angle is well-formed and developed. The mass flow rate required to achieve the desired spray pattern is significantly higher than the design point, even with a relatively limited feeding pressure of 10 bar (it is exhibited a mass flow rate of 19 g/s vs the ideal design was 9.6 g/s). This indicates that additional measures need to be taken to optimize the injector design, ensuring that the desired spray pattern is achieved within the design specifications.

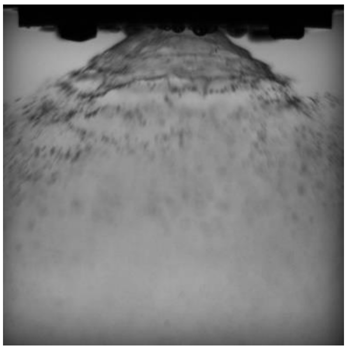

Figure 16 – Test#3, Oxidizer side swirl injector spray pattern at 10 bar feeding pressure. The overall spray cone is reliable, but the mass flow rate generated is more than double the necessary one.

In conclusion of the coaxial swirl study, the comparison between Test #4 and #5 provides valuable insights into the behaviour of both injectors within the prototype. Several observations can be made based on the different outcomes observed.
When both coaxial swirl injectors are tested simultaneously, their spray patterns exhibit distinct behaviour depending on whether the fluids in the two injectors are the same or different. When both injectors operate with the same fluid, such as water, the two individual spray cones quickly merge into a single pattern, resulting in faster atomization. The event can be explained by many theories, including internal fluid stresses connected to the common surface tension, as well as the formation of a low pressure recirculation zone that induces the two cones to collapse in a single one.
The phenomenon is not observed when the operating fluids are different, regardless of whether the two spray cones impinge or not. In Test #5, where different fluids are used in the two coaxial injectors, the two spray cones develop independently, even though they are on a collision course. The overall atomization is still satisfactory, as the impact of the two streams contributes to the atomization of the combined flow. However, it should be noted that this is not how the operations were initially designed and intended.
Analysing more in detail the right-hand side picture of Figure 17, although the spray pattern is promising, the mass flow rates are around 17.4 g/s for the outer (oxidizer) swirl injector and 5.2 g/s for the inner (fuel) swirl injector. While

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the ideal O/F would not be too far from the stoichiometric combustion value, the total mass flow rate would exceed 22.5 g/s, around two times the design point, at a feeding pressure relatively small (10 bar).

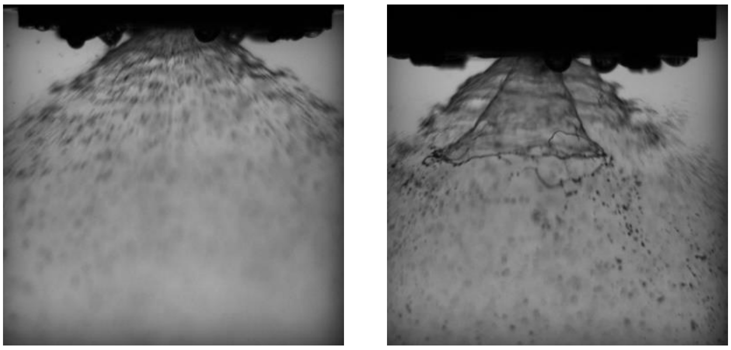

Figure 17 - Test #4 (left-hand side) and Test #5 (right-hand side) at a feeding pressure of 10 bar. Test #5 is the most representative of the ideal designed operations.

Commercial Injectors

As mentioned, it was explored the possible utilization of commercially available components and the selected components have been tested using both water and high viscosity simulant fluid. The tests aimed to study the reliability and spray pattern under different operating conditions than designed. The ideal operating conditions of the components shared by the supplier were different, however it was assured that would generate a reliable spray pattern at any feeding pressure starting from 5 bar.

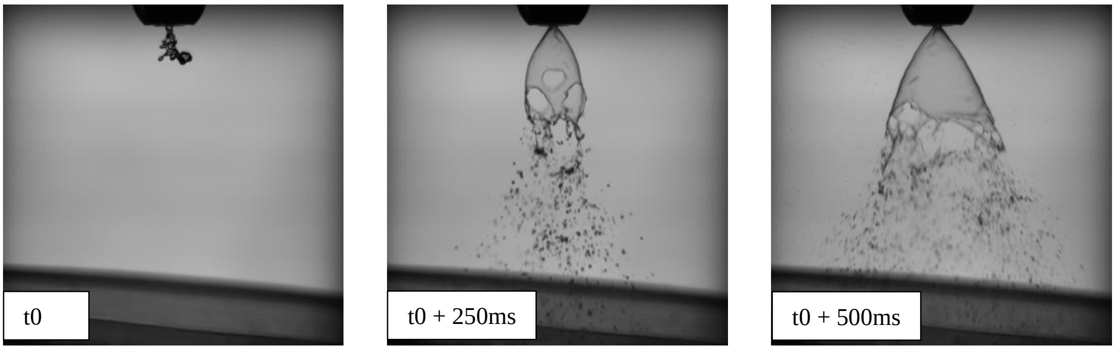

Figure 18 – Spray pattern and transient of commercial injectors - feeding pressure 5 bar.

Figure 18 demonstrates the proven performance of the commercially available components that were tested at the very low feeding pressure of 5 bar and using the high viscosity simulant fluid. Despite the diverse design purposes of these components, they consistently exhibited precise spray patterns when tested with both water and the simulant fluid. Notably, these components also demonstrated a low transient behaviour compared to the other designs, indicating a more stable and consistent operation. The start of the test is determined from the moment the first droplet is emitted from the injector, since it was observed a delay between the opening valve control and the first emission.
The results obtained from these tests highlight the potential of these commercial components for use in the intended application. However, it is important to note that further studies are necessary to gather more information and deepen the understanding of these components. Continued analysis and investigation will contribute to optimizing their performance and ensuring their suitability for the specific requirements of the project.

3.3.3 Swirl – Impinging Hybrid Design – Test results

The design spray pattern, obtained using water in the oxidizer side (spray cone) and the viscosity simulant fluid in the fuel side (impinging streams), is shown in Figure 19.

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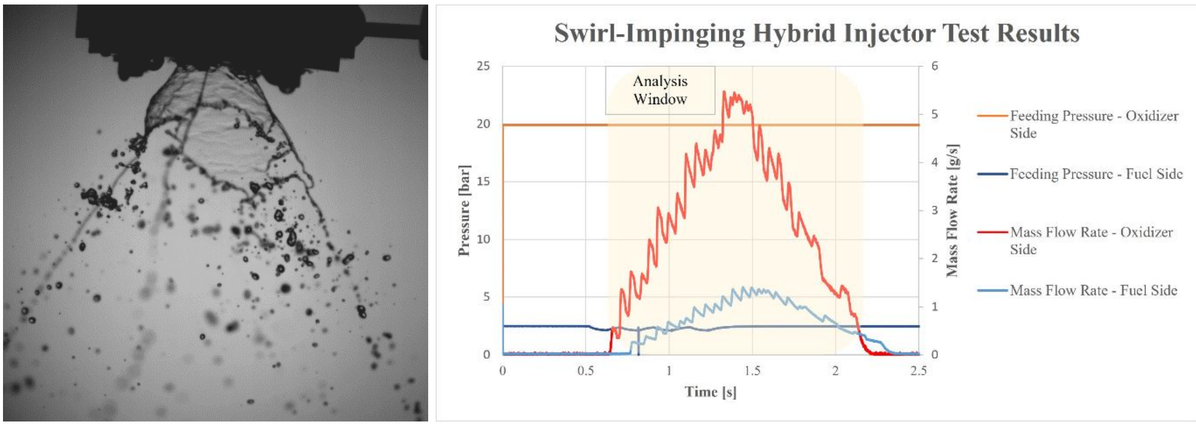

Figure 19 - Spray pattern snapshot and measured features of the hybrid swirl-impinging design

The overall spray pattern snapshot shows promising results. Both propellant components exhibit a satisfactory atomization, and the impinging streams contribute to the mixing process. It is anticipated that the excess oxidizer, visible in figure, will adhere to the walls of the combustion chamber prior the chemical reaction, forming the desired cooling film as envisioned during the design phase. On the other hand, the impinging point of the fuel could lead to hot spots on the chamber wall, where the combustion would concentrate.
Unfortunately, examining the sensor readings it is evident that the injection process lacks stability and exhibits significant oscillations throughout the entire test duration. The mass flow rate does not stabilize to a fixed value in both components and instead is very variable. It is not fully understood the root cause of such an instability, that was not visible from the images taken.
To achieve a visible spray cone for the oxidizer, a relatively high feeding pressure of 20 bar is required, while the fuel necessitates a much lower feeding pressure of 2.5 bar. The achieved mass flow rates, although relatively low, are sufficiently controllable for further testing purposes.
The spray pattern did not show visible transient to reach the conditions pictured in Figure 19. The sensors clearly indicate that the mass flow rate greatly changed and oscillated during the test, however the spray pattern appeared stable in shape and evolution.
The instabilities of measurements make the study of dimensionless number not relevant for this injector design.

4. Conclusions

From the tests, it is possible drawing many conclusions for the proposed injector designs. The conclusions of this study are organized into separate paragraphs dedicated to the various injector designs that were investigated.

- Impinging Injector 4-on-1

The 4-on-1 impinging injector design is a direct evolution of the well-established, tested and performing 2-on-1 design. The spray pattern observed from this design exhibits a large axial momentum, directed towards the nozzle location within the combustion chamber. While the precise characteristics of the mixing process are challenging to predict and visualize, the appearance of a unique spray stream suggests a potentially favourable mixing pattern. However, it is worth noting that the atomization may be partially inadequate in this design. Considering the objectives of the hypergolic engine, the most critical element undoubtedly is the mixing process that initiates ignition and combustion. Consequently, the design was deemed suitable for future ignition tests. However, it is anticipated that the possibly suboptimal atomization could potentially compromise combustion stability and result in rougher combustion characteristics, since the turbulent mixing within the spray stream will be the primary regulating factor. Furthermore, the considerable momentum towards the combustion chamber exit raises the possibility of ignition occurring outside the chamber if the residence time of the propellants inside the thruster is shorter than the chemical reaction (ignition) time.

- Swirl Injectors

Swirl injectors have been extensively tested with water and simulant fluid to validate the design procedure and to visualize the spray pattern obtained.
The test results revealed that, regardless of the feeding pressure, all the designed and tested components required a higher mass flow rate than initially designed to achieve a reliable spray cone. Notably, the spray pattern exhibited by

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the high viscosity fluid demonstrated an elevated breaking length, indicating it requires greater space for proper atomization. This behaviour can be attributed to the reduced Reynolds number resulting from the increased viscosity and low mass flow rate, which induces a laminar flow regime that is less ideal for effective atomization. The influence of viscosity on the fluid behaviour clearly underscores the optimal atomization process.
Analysing the spray pattern of the coaxial swirl design, it is notable that the interaction between the internal and external spray cones is clear and sudden when it is used the same fluid, water, in both the injectors but when different fluids are used in the two injectors, the interaction between the internal and external spray cones is absent, and the cones remain relatively independent, only atomizing upon contact. This behaviour can be advantageous for the intended study objectives. Furthermore, the spray pattern exhibited by the high viscosity fluid has a significantly prolonged transient behaviour, regardless of the feeding pressure and mass flow rate, with a duration of up to 1 second. Additionally, it is worth noting that the desired spray pattern of the high viscosity fluid fails to form altogether under low pressure feed conditions and correspondingly low mass flow rates (below a threshold of approximately 7 bar feeding pressure and 4 g/s, the spray cone is absent).
After careful consideration, it was decided against pursuing the successive hot-firing tests using the swirl injectors due to the excessively high feeding pressure required to achieve satisfactory and reliable operation of the components. The obtained levels of mass flow rate were found to be too large for the dimensions of the prototype. In fact, the total mass flow rate achieved when both injectors exhibited favourable spray patterns, atomization, and mixing exceeded 25 g/s, which is more than double the intended capacity of the hot-firing prototype.
In light of these findings, it was deemed unsafe to proceed with ignition tests using the existing prototype. However, further investigations are warranted to adapt the injector design to better align with the specifications and requirements of the prototype system. These studies will be instrumental in identifying and implementing necessary design modifications to ensure safe and effective operation.

- Swirl-Impinging Hybrid Design

The hybrid swirl-impinging design demonstrated compatibility with operational requirements; however, concern was expressed regarding the repeatability of the injector operation. The spray pattern exhibited some unstable characteristics during the tests, although overall compatible with most of the requirements. Many uncertainties persisted also regarding the propellant mixing and atomization.
It was decided that the design could proceed with very short successive hot-fire tests because its operations are tuneable to the required mass flow rates. The objective of future ignition tests will be to establish whether the new injecting strategy facilitates a stable ignition process and regulates the combustion wall temperature, as predicted during the design.

In summary, several innovative injector designs have been proposed for the existing prototype. The system itself presents a range of complex challenges, primarily associated with the requirement for very low mass flow rates and the physical characteristics of the compounds used as propellants. To assess the performance of the proposed injector designs, a cold-flow testbench was utilized, that allowed the visualization of the spray pattern and the measurement of flow characteristics.
Based on the test results, two designs, namely the impinging 4-on-1 design and the hybrid swirl-impinging design, were selected for further hot-firing tests. Unfortunately, it was deemed unsafe to proceed with ignition tests for the coaxial swirl design in this configuration due to its high mass flow rate relative to the optimal design conditions.
Studying commercially available swirl injectors, designed for different purposes than combustion, the components demonstrated their exceptional reliability in diverse and challenging conditions, surpassing the requirements that other designs could not fulfil. Undoubtedly, conducting further analyses on these injectors will greatly contribute to the advancement of future injector designs.
The analysis of novel injector designs for the hypergolic propellants expanded considering pintle designs [15] that while on one side they increase the complexity of the components, on the other side they could bring enhanced performances and reliability.

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