Ignition of Sprays from Impinging Jets of Green Propellants: Ethyl Alcohol and Hydrogen Peroxide

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Abstract

Current liquid propellants are either cryogenic (storage constraints), either extremely toxic (handling problem). For this purpose, alternative storable propellant are currently being investigated in this work. The sprays generated by a like-impingement configuration have to be ignited. Because the couple of propellants chosen is non hypergolic, the energy of ignition was brought by a torch igniter. The injection conditions of both the propellants and the torch proved to be compatible to ignite the reactants quickly and stabilize the combustion downstream of the impingement point.

Introduction

The need to reduce the environmental impact of propulsion systems has been constant over the past few years. Current storable propellants for spatial applications are rather toxic and manipulating them represents a health concern for the operators. Consequently, the purpose of this study is to evaluate the performances, in particular relative to ignition behavior, of an alternative couple of propellants safer for the human health and with a reduced impact on the environment. The green propellants used are ethyl alcohol and highly concentrated hydrogen peroxide (87.5 % by weight). They are investigated so as to study their ability to be ignited and burned. The emphasis will be on the generative conditions leading to the ignition of this bipropellant system.

Like-doublet injectors can produce droplet sprays, which can be characterized by Phase Doppler Anemometry. A review of the spray phenomenon has been firstly made by Dombrowski et al. [1] and has been recently completed by Bailardi et al. [2].

The theoretical calculations that led to the design of the test bench (which key features will be disclosed) are briefly introduced. The design of the torch igniter is the key parameter of the study because this latter is the way chosen to ignite the bipropellant spray. The elements of the test bench have been validated step-by-step. Then, the ignition of the propellants by the torch has been implemented. High-speed visualizations characterize the behavior of the ignition and the combustion phases.

Experimental setup and specific objectives

To design the current test bench, preliminary tests were performed to characterize a like-impingement spray. In particular, the Sauter Mean Diameter (SMD) was experimentally determined thanks to PDA among a 2 000-droplet water spray. Several correlations were studied in parallel so as to know which one would fit the best to our configuration [3] - [5]. Finally, the Ramamurthi correlation [5] was chosen to estimate theoretically droplet diameters. This estimation was the key point for the design of the present test bench. The angle of impingement was set to 60° whereas the number of doublets and the orifice diameter were to be chosen. A stoichiometric liquid equivalence ratio was targeted so as to make the ignition easier. The evaporation response of the propellant is taken into account with various empirical data concerning ethyl alcohol and hydrogen peroxide (saturated vapor pressure, and droplet temperature for example) [6], [7]. The estimations are given considering the assumptions of the Spalding theory [8]. Extensive studies for droplet evaporation in a dense spray or in transient state are given in [9] - [11]. Again, a stoichiometric gaseous equivalence ratio is the theoretical goal and would significate that all the liquid has been vaporized. However, even if the like configuration suggests it, no mixing model between both propellants has been included to the study, because it is essentially an experimental work. The mixing mechanisms are discussed in [12], [13].

The nominal configuration was set as follows, because it allows moderate total flow rates (discharge coefficient of 0.85), and a liquid equivalence ratio near 1. The injector plate (Figure 1) is composed of one central spray of ethyl alcohol, surrounded by two sprays of hydrogen peroxide. Thanks to the small space between each doublet and the conical shape of the sprays, fuel and oxidizer may interact downstream of the impingement point.

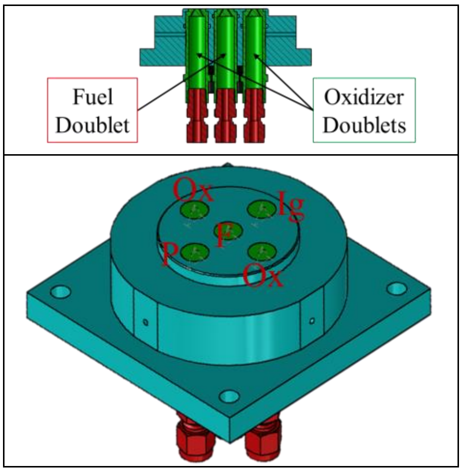

Figure 1: The injector plate fitted with injectors of oxidizer (Ox) and fuel (F), and the slots for the torch igniter (Ig) and the pressure sensor (P)

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Several elements are added to help the ignition occur. First of all, a hydrogen-air torch igniter is designed. Its characteristics are resumed in Table 1:

Table 1: The torch igniter parameters

Inlet pressure (bar)	4
Throat diameter (Air) (mm)	1.60
Throat diameter (H_2) (mm)	0.50
Total flow rate (g/s)	1.48
Equivalence ratio φ	0.88
Ejection throat diameter (mm)	3.50

Consequently, the interaction between the torch igniter and the propellant sprays is also investigated. We compare the ability of the sprays to be ignited using different geometries of the torch igniter that permit to eject either burnt gases or a flame, orientated towards the sprays of our propellants or straight on.

Then, a tube included around the injector doublets serves as a combustion chamber (Figure 2 and Table 2). It enables the rise in temperature and maintains a warm environment after each run of the torch. A throat (Figure 2 and Table 2) has been implemented at the tube exit to allow a moderate rise in pressure inside the tube, but especially for creating recirculation zones in the tube. It has been designed so as to reach a Mach number of around 0.25 at the throat.

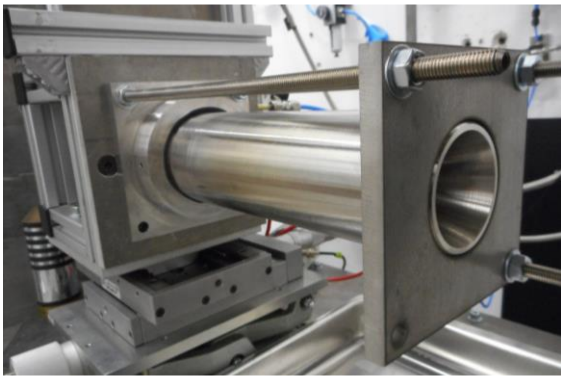


Figure 2: The combustion chamber before the experiments

Table 2: The combustion chamber parameters

Length L (mm)	200
Inner diameter D (mm)	58
Throat diameter D_t (mm)	30
Throat divergent angle θ (°)	20
Throat Length L_t (mm)	30
Material	Steel

In addition, high-speed color visualizations (Phantom V310, 300 fps, 3300 μs of exposure time, aperture f/8.0) are achieved at the exit of the throat to identify the length of the flame. Pressure measurements for the propellants injection (GEMS Sensors 3100 series, piezoresistive, 0-40 barG, 0.25 % accuracy) and for the dynamic pressure inside the chamber (Kistler 601A, piezoelectric, -15.6 pC/bar sensitivity, 0.5% accuracy) are implemented. The Phase Doppler Anemometer system is PDI-200 MD (Artium Technologies; Focal Lengths: 500 mm; Fringe spacing: 4.33 mm; Estimated accuracy and resolution: +/- 0.5 mm).

Some test campaigns are performed and compared. Firstly, ignition tests of ethyl alcohol sprays in stagnant air are carried out. Then, ignition experiments of both ethyl alcohol and hydrogen peroxide sprays in the ambient environment (the tube) are conducted. For these series of tests, the nominal liquid ratio is 1.1 (*Table 3*). Another theoretical value of around 0.9 serves as comparison. The operation time of the torch igniter, is a parameter of interest for the study. It has to be as short as possible but long enough to ignite and stabilize a combustion phase of the spray mixture. Its mass flow rate represents around 10 % of the total propellant mass flow rate, and has an effect on the length of the flame. Consequently, for the interaction test between the torch and the propellants, two different cases were conducted: the first was performed with the torch running throughout the injection time whereas for the other test, the torch was cut off during the propellant injection time (1 second after the injection trigger) while the propellant were still flowing during 1 or 3 seconds. The behavior of the flame exiting the tube is compared.

Results

The distributions of droplets generated by the like-doublets were characteristic of a spray. All their shapes were similar to the following ones (Figure 3 to Figure 5):

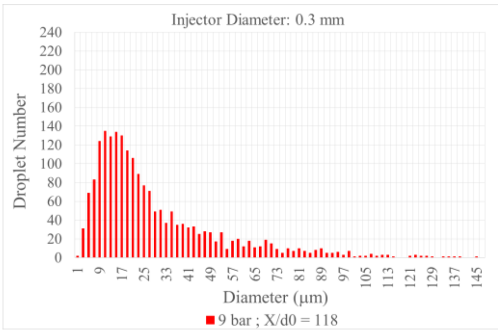


Figure 3: Histogram for one 0.3 mm injector at 9 bar water pressure

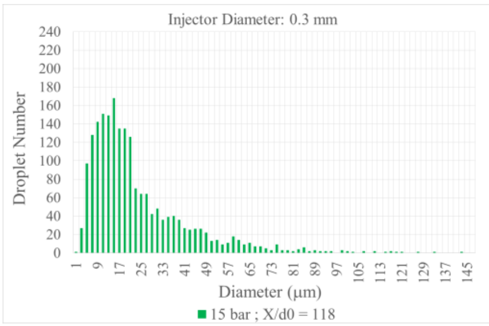


Figure 4: Histogram for one 0.3 mm injector at 15 bar water pressure

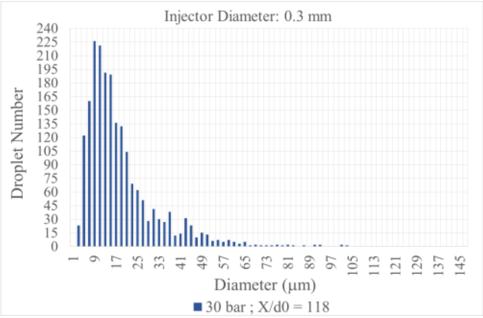


Figure 5: Histogram for one 0.3 mm injector at 30 bar water pressure

The red, green and blue distributions refer respectively to a pressure drop of 9, 15 and 30 bar. From this point, we can conclude that a higher pressure gives more homogeneous distributions because the peak of the associated histogram exhibits a thinner width (along diameter axis) and a higher amplitude (along droplets count axis) for increasing pressure.

Figure 6 includes the data concerning the Sauter Mean Diameter (SMD) values associated to the 4 injectors available of 0.3 mm diameter.

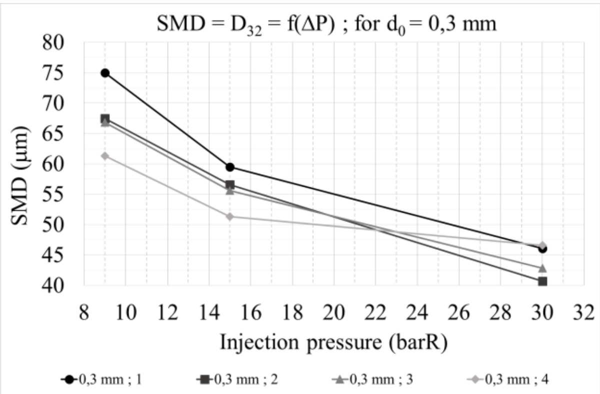


Figure 6: SMD as a function of water injection pressure for 4 injectors of 0.3 mm diameter

The discrepancy between the injectors could be linked to the drilling (average discrepancy of 18 % between the minimum and maximum values). The increase in injection pressure contributes to the decrease in the SMD.

The correlation chosen to estimate the SMD of the current test bench is the one of Ramamurthi et al. [5].

$$\frac{SMD}{d_0} = 1.15\, S^{-1/6} We^{-1/3} \quad , \quad with\ S = \frac{\rho_{gaz}}{\rho_{liq}}$$

where d_0 is orifice diameter, ρ is the fluid density, and the Weber number: $We = \frac{\rho_{liq} V^2 d_0}{\sigma_{liq}} = \frac{2\Delta P d_0}{\sigma_{liq}}$

Obviously, the main parameter which drives the SMD is the orifice diameter: the smaller the orifice diameter, the smaller the SMD.

The nominal configuration described in the previous part is the one in Table 3 and can lead to a liquid equivalence ratio of 1.10.

Table 3: The nominal configuration for the experiments in reactive conditions

Parameters	Unit	Value	Ratio of Ox./Fuel Values
Fuel Pressure	*bar*	3	3.3
Ox. Pressure	*bar*	10	
Fuel Diameter	*mm*	0.3	1
Ox. Diameter	*mm*	0.3	
Fuel Doublets Number	*[-]*	1	2 nozzles per doublet
Ox. Doublets Number	*[-]*	2	
Total Fuel Flow Rate	*g/s*	2.6	4.8
Total Ox. Flow Rate	*g/s*	12.6	
Total Flow Rate	*g/s*	15.2	
Liq. Equivalence Ratio φ_{liq}	*[-]*		**1.10**

The following assessments have been explained in [14].The difference of volatility of the two propellants make the ignition impossible at 25°C because only the ethyl alcohol can vaporize. The theoretical equivalence gaseous ratio would be 104… At 100°C, the gaseous equivalence ratio is still high: it amounts to 4.0. At higher temperature, the hydrogen peroxide tends to evaporate easier. So, if the torch igniter can maintain the environment at a minimum temperature of 150°C, the estimations of diameters and evaporation times give (Table 4):

Table 4: Diameters (based on Ramamurthi correlation) and evaporation times estimations in the nominal configuration, and the ratios of oxidizer to fuel values (last column)

Fuel SMD (150°C)	*µm*	50	**1.2**
Ox. SMD (150°C)	*µm*	59	
Fuel Evap. Time (150°C)	*ms*	48	**0.2**
Ox. Evap. Time (150°C)	*ms*	10	

The torch igniter is included in the injector plate through one of the available slot as illustrated in Figure 7.

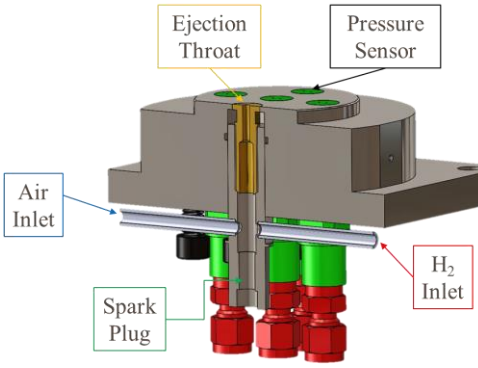


Figure 7: The torch igniter inserted in an available slot of the injector plate

The interaction between the inclined ejection throat and the sprays is studied (Figure 8). When the torch is running, the central spray is deflected as shown in this inert test:

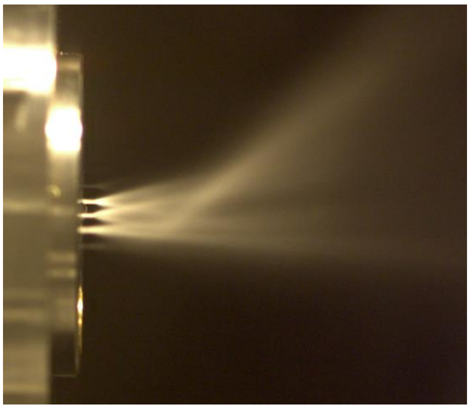


Figure 8: The effect of the torch igniter on the central spray (non-reactive conditions)

The throat directed toward the propellants allows a better interaction with the central spray (Figure 9).

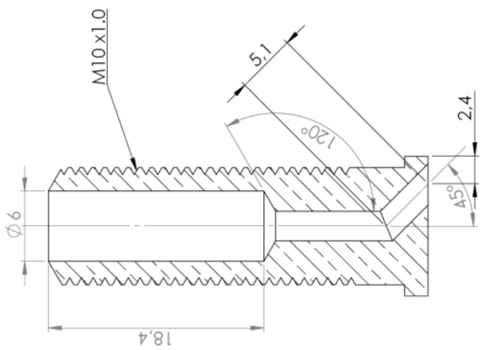


Figure 9: The inclined ejection throat

Figure 10 represents a typical chronogram for a complete combustion test:

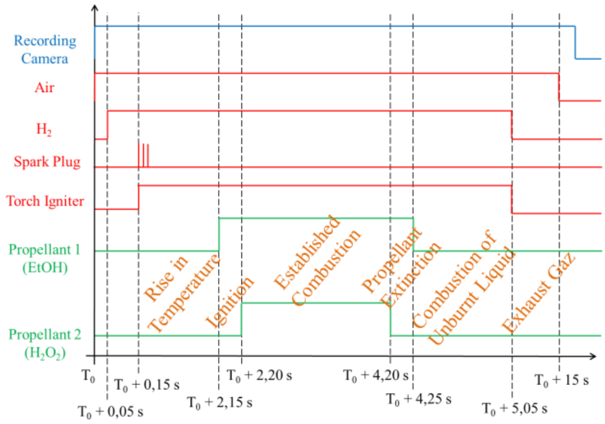


Figure 10: The short-time propellant injection chronogram

The physical conditions of the different tests performed are resumed in Table 5:

Table 5: Physical condition for all the tests performed

Test number	1	2	3
Specificities of the test	Short-time Fuel rich	Short-time Fuel lean	Long-time Fuel rich
φ_{liq}	1.10	0.86	1.10
P_{EtOH} (bar)	3	2	3
P_{H2O2} (bar)	10	11	10
ϕ_{EtOH} (x1) (mm)	0.30	0.30	0.30
ϕ_{H2O2} (x2) (mm)	0.30	0.30	0.30
Propellant Injection Time (PIT) (s) EtOH/H_2O_2	2.1/2	2.1/2	4.2/4
Torch Igniter during PIT	2.1	2.1	1
Total mass flow rate (g/s)	15.2	15.3	15.2

As mentioned in Table 5, the goal was to obtain an equivalent total mass flow rate. For all the previous conditions, the combustion tests exhibits a flame at the exit of the throat, which means that the tube is not long enough to maintain the combustion inside it.

High-speed visualizations give some information on the flame behavior. The same image processing has been employed to the following images.

The first two images (Figure 11 and Figure 13) of the flame compare the theoretical liquid equivalence ratio for two tests at the same time (only a 2 ms difference). Apparently, the light intensity is higher for the presumed fuel-lean condition. The length of the flame does not seem different between both images. Dynamically speaking and assuming the total flow rate does not change, the length is more or less constant, except during ignition or other unsteady phases.

Figure 11: Conditions of test n°1

Pressure signals are recorded during each test to get the chamber pressure and the nitrogen pressurization of the propellants. Figure 12 corresponds to the nominal condition experimented. The opening of the propellant valves induce a maximum pressure drop of about 0.5 bar for H_2O_2 and less for ethyl alcohol. That can be explained by the flow rate and the greater absolute value of 10 bar for H_2O_2. Despite this pressure drop, the injection pressure is stabilized for both propellant. The combustion phase occurs quasi simultaneously with the injection opening.

The chamber pressure rises suddenly, oscillates and reaches a constant level. The pressure rise in the chamber reaches around 30 mbar, which corresponds to a velocity of about 260 m/s. This value is consistent with the Mach number targeted of 0.25.

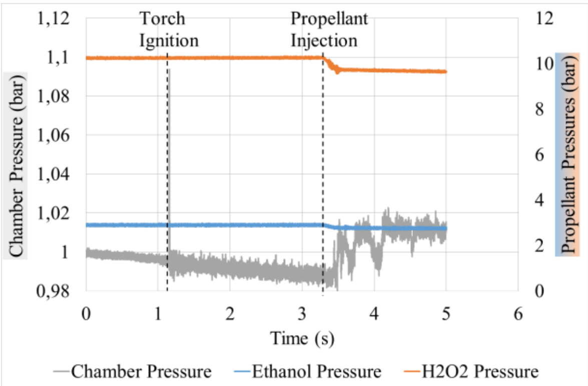


Figure 12: Pressure signals in the chamber and for the propellants (test n°1)

Figure 13: Symmetrical flame (conditions of test n°2)

In most cases, the flame is symmetrical (Figure 13).

But, because of a poorer impingement quality, a proportion of the propellants may not be ignited, which would result in an unsymmetrical flame as shown in Figure 14 and explained with the non-reactive conditions in Figure 15. This phenomenon is uncontrolled and intermittent. It results in a bad atomization and is linked to the difficulty to drill such thin impinging doublets.

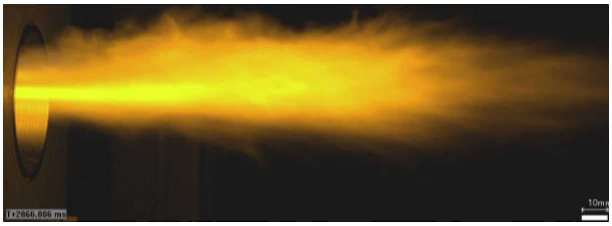


Figure 14: Unsymmetrical flame (conditions of test n°2)

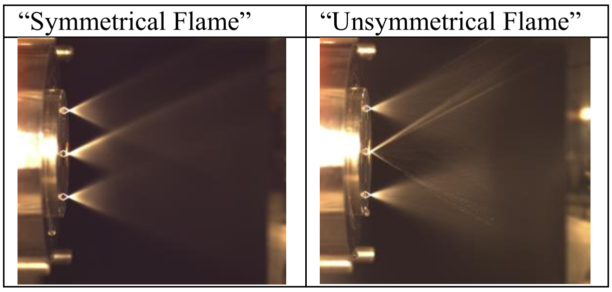


Figure 15: Potential relation between the jet quality of impingement and the flame structure

The last two images (Figure 16 and Figure 17) show the effect of the torch igniter on the flame of the two propellants. These images are extracted from the same test. The time difference between the two is approximately 0.333 s. In the former image, the torch is running whereas in the latter, it has been cut off. Doing so, the combustion is self-sustained during more than 3 seconds. The torch igniter seems to be coupled to the flame dynamics. It shortens the flame dramatically, probably due to the presence of the hydrogen flame in the chamber.

Figure 16: Conditions of test n°3 (the flame while the torch is working)

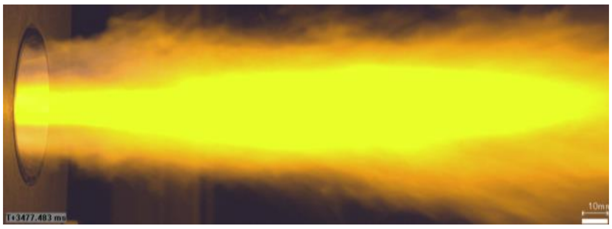
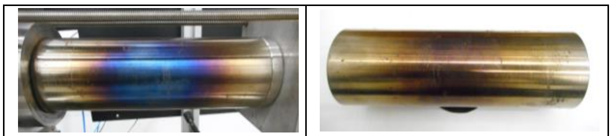


Figure 17: Conditions of test n°3 (the flame while the torch is cut off)

Figure 18 allows us to estimate the temperature distribution inside the tube and also the ignition location (the blue color indicates a local temperature of around 1500 K). The ignition seems to occur in the middle of the tube. Then, the flame radiation and tube conduction seems to spread symmetrically all along the tube. Compared to the tube wall, the injector plate does not seem to have suffered from the radiation and oxidation (Figure 19).



"Half part directly exposed to the torch"	"Opposite half part of the tube"

Figure 18: Combustion chamber after the series of experiments (temperature distribution)

Figure 19: The injector plate after the experiments

Conclusion

Ethyl alcohol and highly concentrated hydrogen peroxide (87.5 % by weight) can be ignited and burnt together with the injector plate equipped with a torch igniter. Moreover, the combustion phase can be stabilized at least during the time tested (3 seconds) with the torch cut off.

The torch igniter has a strong effect on the behavior of the flame: the latter gets longer without the torch running, which means the flame and the burnt gases of the torch tend to accelerate the chemical rate of the combustion of the two propellants.

The impingement quality is also of paramount importance because if the quality worsens, the combustion cannot be uniformly spread on a section of the tube. Consequently, the flame can be unsymmetrical, and the proportion of unburnt propellants rises.

The next step for the test bench is to substitute the tube by another which would enable optical access inside the combustion chamber. A spectrometer will be included so as to evaluate the spectral composition of the flame at the exit of the chamber.

Acknowledgments

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