DOI: 10.13009/EUCASS2017-233



# Combustion of sprays from triplet injector with green propellants: ethyl alcohol and hydrogen peroxide

*Clément Indiana*, Bastien Boust*, Marc Bellenoue* and Nobuyuki Azuma***
** Institut Pprime, CNRS/ISAE-ENSMA/Université de Poitiers*
*Chasseneuil-du-Poitou, France*
*** Japan Aerospace Exploration Agency (JAXA)*
*Japan*

**Abstract**
PPRIME and CNES are investigating the combustion of green storable propellants without catalyst, using jet-impingement injectors to characterize their atomization and combustion. In the present study, triplet injectors are introduced for expecting shorter mixing length. Spray imaging, droplet sizing and combustion visualization are performed on triplet injectors. Triplet combustion performance is finally compared to that of doublet injectors in terms of characteristic velocity efficiency.

## 1 Introduction

There is a growing need to investigate green alternative storable propellants for space thruster applications. Among the advantages of such green propellants, the human health and environmental impact are paramount. But safe green propellants also have to allow propulsion performance and ignitability, as well as re-ignition capability.
Former studies about green propellants deal with hypergolic systems [1]-[3], or staged decomposition combustion [4]-[6] that requires decomposing H2O2 into oxygen and water vapour in a catalyst before burning with the fuel in the combustor. PPRIME Institute and CNES are currently investigating storable propulsion based on non-hypergolic, non-catalytic combustion. For this purpose, a lab-scale facility ACSEL [7]-[8] has been developed to allow optical diagnostics and a high degree of modularity. In this work, a green bipropellant system is investigated, namely ethanol and hydrogen peroxide, with two kinds of impinging-jet injectors: a like-on-like doublet configuration, as well as an unlike triplet injector. The present study aims at characterizing the spray properties of such injectors, and their combustion performance.

## 2 Experiment and diagnostics

### 2.1 Experimental setup

In this study, a reference couple of green storable propellants is implemented: High-Test Peroxide (HTP) is used as an oxidizer, and ethanol as a fuel (see Table 1); given the concentration of propellants, the stoichiometric mixture ratio MRst is 5.01. These two propellants are miscible.

Table 1: Propellants used in this study

| Propellant | Product | Concentration | Molecular weight (g/mol) | Density (kg/L) |
|---|---|---|---|---|
| Oxidizer (Ox) | HTP875 | 87.5 %m | 30.5 | 1.376 |
| Fuel (F) | Ethanol | 99 %m | 45.4 | 0.790 |

ACSEL test bench is made of an injector, a cylindrical combustion chamber and a throat (see Figure 1). A torch ignitor (referred to as “Ig” on the schematic) is set inside the injector plate. In this study the throat diameter is set to

DOI: 10.13009/EUCASS2017-233



7 mm. The modular structure of ACSEL test bench provides the possibility to operate either with an optical combustion chamber (length L/L° = 1), or with a shorter opaque chamber (length L/L° = 0.2).

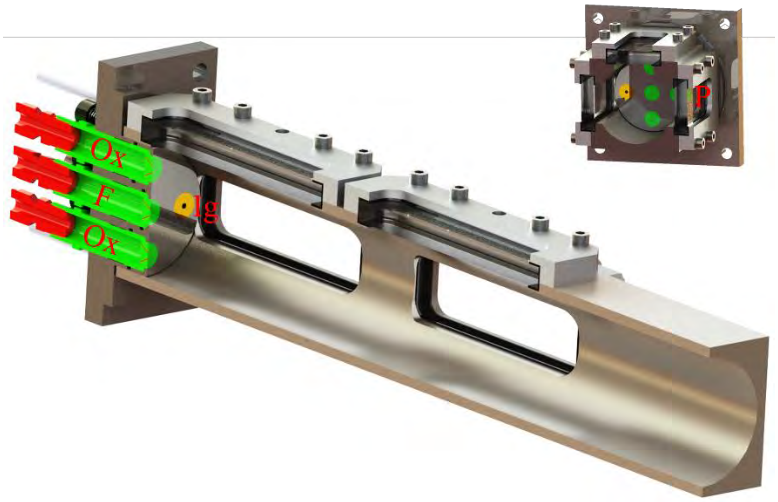
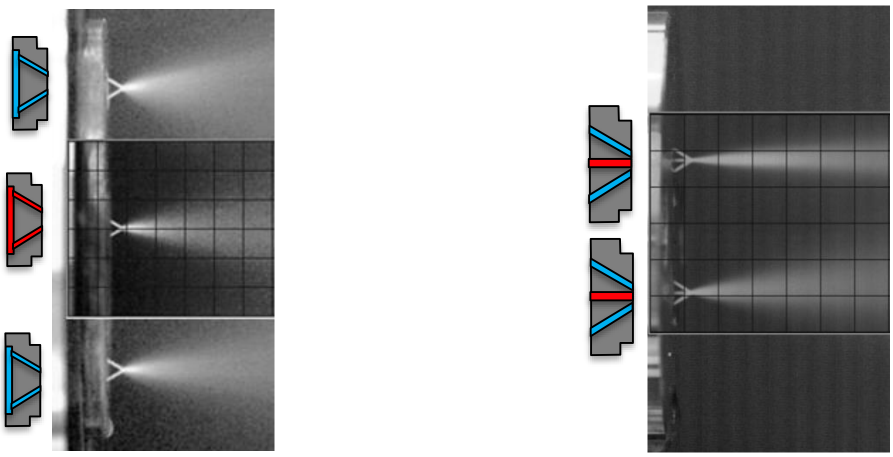



Figure 1: Schematic of ACSEL optical combustor including like-doublet injector – L/L° = 1

The injectors considered in this study represent two distinct configurations based on impinging-jet injectors (see Figure 2). The first configuration is a like-on-like doublet injector: two oxidizer doublets and one fuel doublet generate separate sprays downstream the injection plate. The second configuration is made of two unlike-triplets where each triplet is made of a fuel jet impinging on a like oxidizer doublet. In this study all liquid jets are of the same diameter: d = 0.3 mm.
Propellants are fed into the injector through inert gas pressurization up to 4 MPa, using pressure regulators.



a) b)

Figure 2: Distribution of fuel jets (red) and oxidizer jets (blue) for the two injectors considered in this study: like doublets (a), unlike triplets (b). The squared region corresponds to optical access.

Unlike most bipropellant systems that use a catalyst bed for ignition, in our study a GH2-air torch is used to initiate the combustion of propellants injected in liquid phase In this work, the torch thermal power is limited to 15% of the total mass flowrate, and it is stopped to perform combustion measurements in self-sustained conditions (see Figure 3). This prevents any influence of the ignition device on combustion behaviour.

DOI: 10.13009/EUCASS2017-233



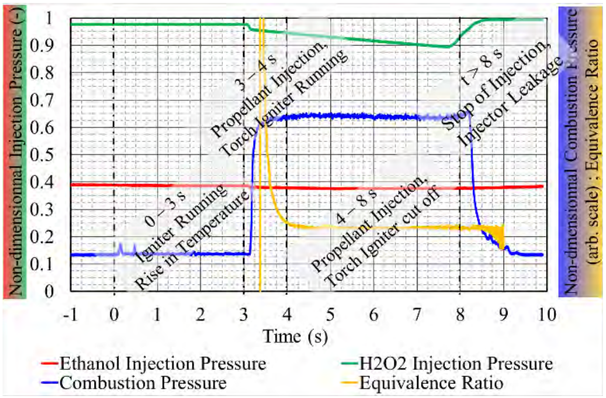



Figure 3: Time chart of a typical ACSEL combustion test

## 2.2 Spray diagnostics

The sprays generated by the specific injectors described above (see Figure 2) are characterized using a dedicated facility adapted to particle sizing and visualization (see Figure 4). Propellants are replaced by water for safety purposes, and fed through the injector using the same process (inert gas pressurization) as in ACSEL.
First, spray visualization is carried out using back-lit shadowgraphy (Photron Fastcam AX200 combined with LED HI-LIGHT-8 plate). Particle sizing is also performed thanks to a commercial Phase-Doppler Interferometer system (PDI-200 MD, Artium Technologies). It provides the distributions of particle diameter and velocity.

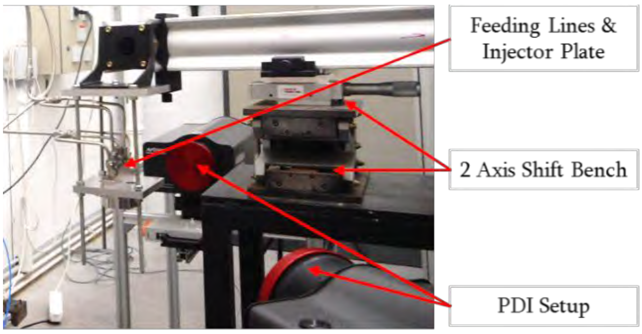



Figure 4: Non-reactive test bench for spray diagnostics

## 2.3 Combustion diagnostics

Injectors are instrumented to characterize the propellant flow properties: pressure (piezoresistive sensor, precision 0.25%) and mass flow rate (Coriolis flowmeter, precision 0.2%). The combustion chamber is instrumented with time-resolved diagnostics to characterize the reactive flow: combustion pressure (Kistler 601A, precision 0.5%, bandwidth 150 kHz), and direct visualization (camera Phantom v310, 12 bit). Such diagnostics are expected to capture the dynamics of combustion reactive flow.
Experimental measurements provide the combustion performance, through the characteristic velocity c*, and its efficiency ηc* (see Eq. 1). The ideal burned gas properties are evaluated using CEA computation code [9].

$$\eta_{C^*} = \frac{c^*}{c^*_{th}} \qquad c^* = \frac{P_{cc} A_{throat}}{Q_{cc}} \qquad c^*_{th} = \sqrt{\frac{rT_b}{\gamma_b} \times \left(\frac{2}{\gamma_b - 1}\right)^{\frac{-(\gamma_b+1)}{2(\gamma_b-1)}}} \quad \textbf{(1)}$$

DOI: 10.13009/EUCASS2017-233



# 3 Results and discussion

## 3.1 Characterization of the spray of each injector

Each injector is characterized with water using back-lit shadowgraphy (see Figure 5). In like-doublet configuration, water pressure is of 0.9 MPa. For the unlike-triplet injector, the central jet (featuring the fuel) is fed at 0.9 MPa vs 3.0 MPa for the outer jets (oxidizer). Indeed, the unlike triplet is run with different pressure levels, corresponding to realistic injection conditions (near-stoichiometric mixture ratio).
The spray shape of unlike-triplet is quite similar to that of like-doublet injector, that is already described in our latest work [11]. A wavy liquid sheet is created at the impingement point and primary breakup creates ligaments that, in turn, generate small droplets at secondary breakup. As far as spray topology is concerned, the addition of the central jet does not seem to affect significantly the spray generated by the doublet. This will make comparison easier between the two injectors. Besides, the impingement of the 3 jets at the same point compensates for possible misalignment of the jets, that may be due to hole machining and affects significantly the atomization of like-doublets [10].
Since the triplet injector is partly based on the same geometry as the doublet injector, a verification test is performed by flowing only the two outer jets with water, without the central jet. This generates the same spray as the doublet, as expected.

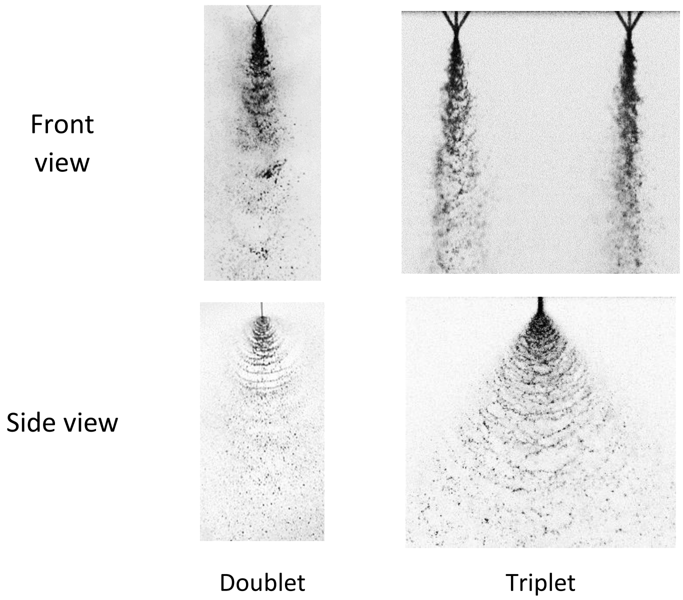



Figure 5: Injector sprays: doublet (pressure 0.9 MPa) and triplet (0.9 MPa central jet vs 3 MPa outer jets)

The distribution of drop size and velocity is evaluated by Phase-Doppler Interferometer in a separate setup featuring the same injection process as ACSEL, but without combustion [10]. According to this study, the drop size distribution is characterized by the Sauter mean diameter depending on injection pressure drop $\Delta P$ and measurement location X/d (see Figure 6Figure 5). For the sake of simplicity, the triplet spray is operated firstly in like-pressure conditions. When the injection pressure drop increases, the jet velocity increases and the SMD decreases as a result of the impingement process for both doublet and triplet injectors. Compared to the SMD of doublet spray (considered as reference), the triplet spray yields a lower SMD at most pressure drops. The evolution versus X/d is also investigated: SMD decreases slightly along the spray centreline from the impingement point; except at location X/d = 50, inside the dense spray region that does not allow reliable measurements.

DOI: 10.13009/EUCASS2017-233



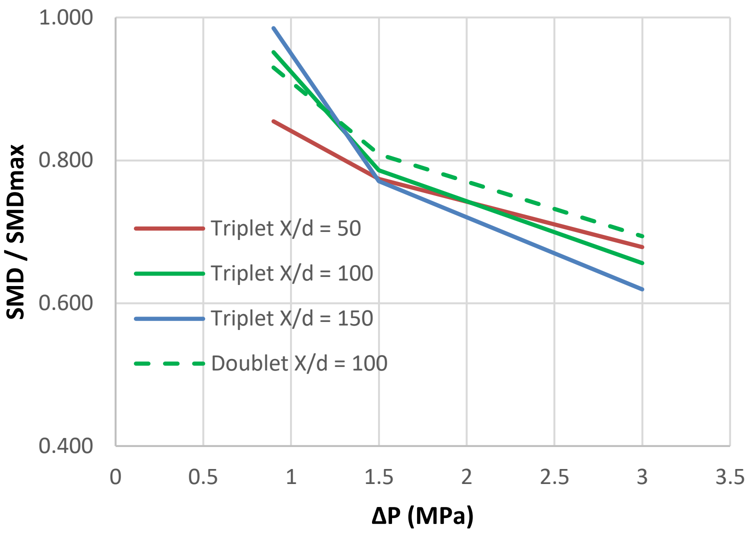



Figure 6: Distributions of SMD along the spray centreline in like-doublet (reference) and like-triplet injector – Water

The drop size and velocity distributions are also investigated for conditions representative of bipropellant injection. For this purpose, the triplet is operated in unlike-pressure conditions for variable pressure drop and fixed X/d = 100 (see Figure 7). As pressure drop increases, the mean droplet velocity increases and SMD decreases, leading to better atomization and penetration. The behaviour of the triplet injector is similar to that of like-doublet. In unlike-pressure operation of the triplet injector, the spray properties do not seem to be affected by the contribution of the central jet (fuel), as already seen on the shadowgraphy pictures (see Figure 5). To sum up, the spraying process of the like-doublet and unlike-triplet injectors is obviously governed by the impingement dynamics of the two outer jets.
Regarding the injection of propellants inside the combustion chamber, these results confirm the interest of the unlike-triplet. Indeed, doublets generate separate oxidizer and fuel sprays, hence a heterogeneous fresh mixture in terms of drop size, velocity and equivalence ratio. On the contrary, the triplet spray is composed of mixture with homogeneous properties, and its induction length may be reduced compared to doublet injector.

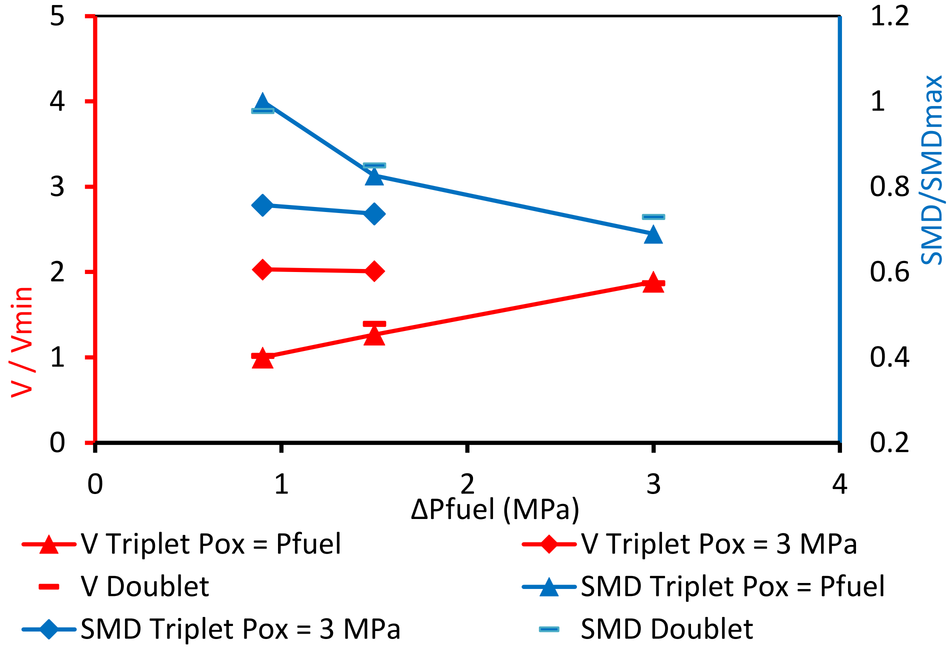



Figure 7: Distributions of SMD and mean droplet velocity in doublet (reference) and triplet injector – Water, X/d = 100

DOI: 10.13009/EUCASS2017-233



## 3.2 Combustion behaviour and stability

The results presented hereafter were obtained using ACSEL facility in stable operation conditions, after the torch extinction. The two injector configurations, either like-doublet or unlike-triplet, led to satisfactory ignition and self-sustained HTP-ethanol flames, as described in detail earlier [7]-[8]. In the following, results are normalized by reference values denoted as "°", e.g. ER/ER° for the normalized equivalence ratio.
Combustion behaviour is firstly described through high-speed visualizations of the reactive flow inside the combustion chamber (see Figure 8). The yellow colour is caused mainly by the spontaneous emission of sodium at high temperature, that is one of the stabilizing products of HTP. Therefore, this yellow colour is a reliable indicator of the flame location, as it is related to the high-temperature reacting gas.
Obviously, the turbulent diffusion flame is lifted off the doublet injector plate, whereas it is attached to the triplet injector plate. As opposed to the flame that develops in the mixing zones generated downstream of the sprays of the doublet injector, it is noticeable that the flame is anchored to the impingement point of the triplet injector. This is consistent with the above results of the atomization study: the combustion of miscible bipropellants is favoured in triplet injector because mixing occurs at a controlled location, which shortens the induction length.
The flame emission of triplet configuration is almost uniform at a distance of about 60 mm from the injector plate (see dashed line on Figure 8). On the contrary, a dark zone indicating incomplete combustion remains at this position with the doublet injector. Thus, this critical chamber length seems to be sufficient for the triplet injector to allow for complete combustion of the propellants at stake, whereas the doublet injector requires a longer chamber.

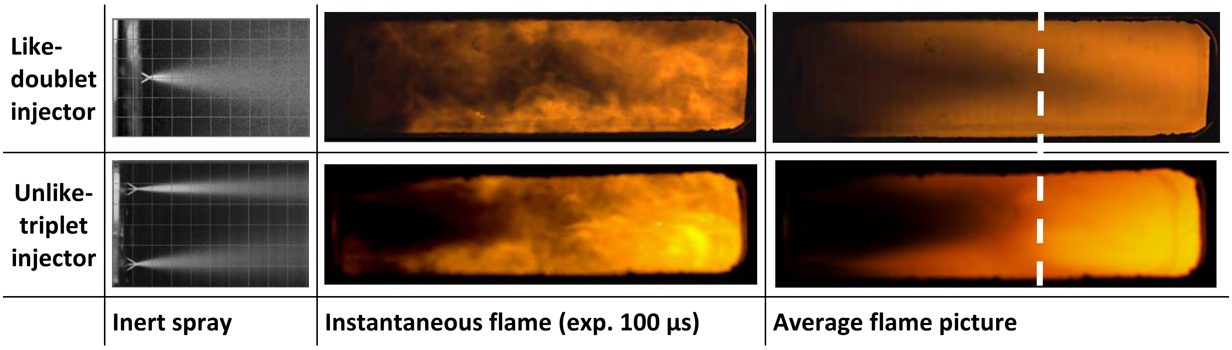


Figure 8: Comparison of the flames generated by doublet and triplet injector sprays – L/L° = 1, ER/ER° = 0.48

The evolution of this combustion process is observed in the triplet configuration for varying equivalence ratio at fixed mass flowrate (see Figure 9). In this process where mixing occurs from the impingement point, the effect of combustion chemistry is evidenced: the flame is attached at low ER, and gradually separates from the injector plate at highest ER. This statement highlights the importance of equivalence ratio distribution inside the combustor, even though HTP-ethanol combustion is clearly robust to a wide range of equivalence ratio, varying by 4:1 in this case.

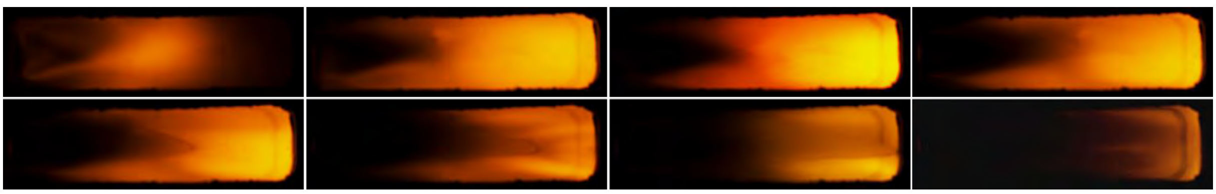
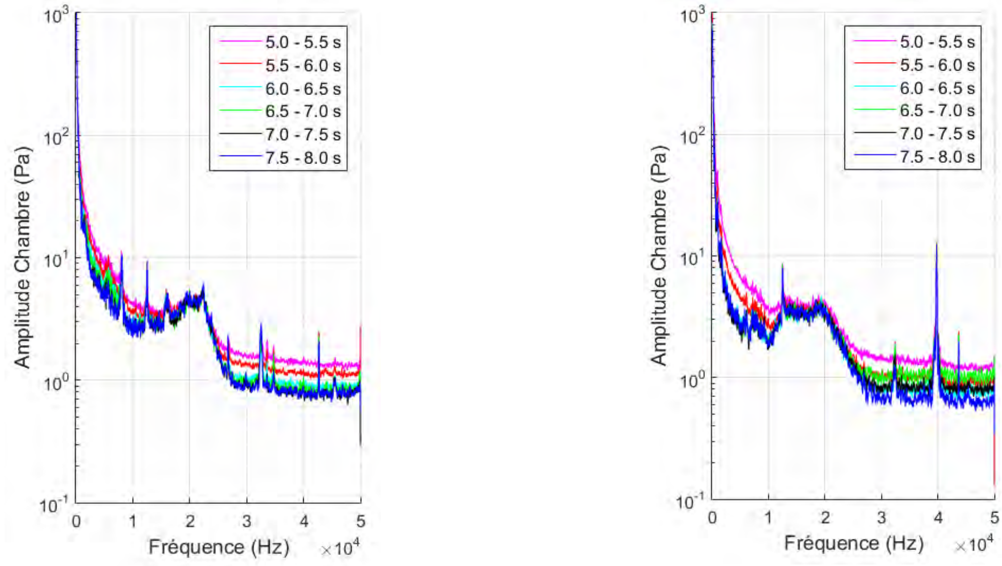


Figure 9: Average flame pictures of unlike-triplet injector at fixed mass flowrate – Length L/L° = 1; Ranging from left to right, ER/ER° = 0.25 – 0.34 – 0.42 – 0.48 – 0.53 – 0.64 – 0.74 – 1.0

The stability of this combustion process is also characterized thanks to dynamic pressure measurements (see Figure 10). Both injectors exhibit a similar pressure spectrum, and the peaks of the spectrum do not exceed 10 Pa. This confirms the stability of the turbulent combustion flame inside the combustor, either for the doublet or triplet injectors.

DOI: 10.13009/EUCASS2017-233






Like-doublet injector

Unlike-triplet injector

Figure 10: Pressure spectrum along time during the combustion phase for doublet and triplet injectors.

## 3.3 Combustion performance

The experimental results gathered on the doublet and triplet configurations allow their comparison in terms of combustion performance, through the characteristic velocity c* and its efficiency ηc* (see Eq. (1)). For both injection configurations, combustion efficiency follows a similar curve versus equivalence ratio with a maximum due to stoichiometry (see Figure 11). The combustion efficiency of triplet injector reaches an equivalent magnitude and evolution as the doublet injector, with approximately the same dispersion.

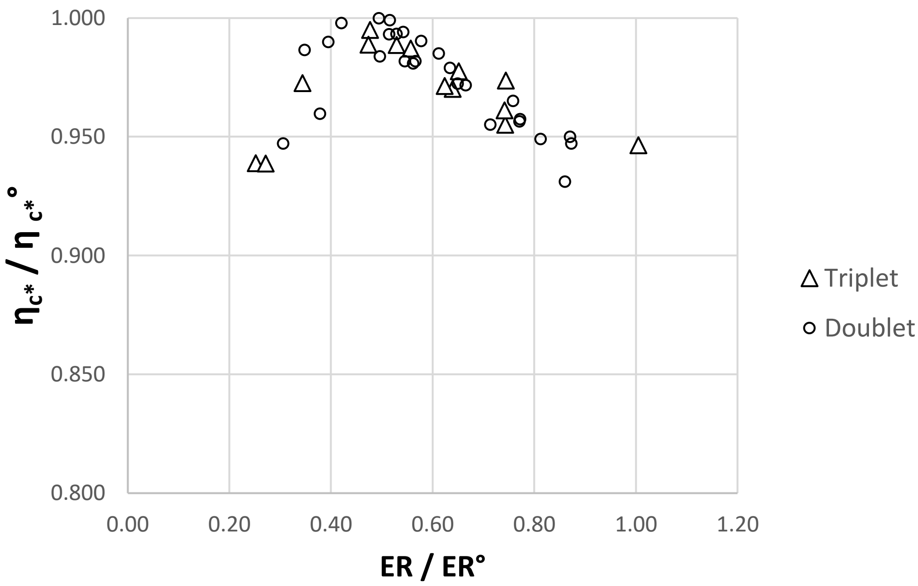



Figure 11: Evolution of characteristic velocity versus equivalence ratio – L/L° = 1

DOI: 10.13009/EUCASS2017-233



Obviously, the optical chamber length L/L° = 1 makes it difficult to quantify the difference between triplet and doublet injector performance. Thus, the shorter opaque chamber is operated so as to use the two injectors in more severe conditions regarding the chamber volume: its length is L/L° = 0.2, that is slightly larger than the critical length of 60 mm at which combustion is complete for the triplet injector only (see dashed line on Figure 8).

For the combustion experiments carried out in this short opaque chamber, the optimum combustion efficiency ηc* is decreased strongly (-12%) in the case of the doublet injector, whereas it is hardly decreased (-2%) in the case of the triplet injector. Due to this decrease in chamber volume, the residence time is no longer sufficient to allow for mixing and combustion in the doublet injector case. The reduction of chamber length does not affect combustion efficiency in the case of the triplet injector, therefore this configuration is more efficient for mixing and spray combustion.

## 4 Conclusion

The combustion of ethanol in combination with HTP has been investigated in non-hypergolic, non-catalytic conditions. For this purpose, a lab-scale facility ACSEL has been operated with two kinds of injectors: like-doublet and unlike-triplet. Experiments reveal the injection and combustion behaviour of these two configurations.

From visualization and PDI spray analysis, it seems that triplet spray has homogeneous properties with direct mixing of fuel and oxidizer at the impingement point, whereas doublet sprays of fuel and oxidizer require a longer induction zone for mixing. Combustion visualization shows that in most conditions the flame is anchored to the triplet injector plate, whereas it is lifted off the doublet injector plate.

Combustion performance is evaluated over a wide range of equivalence ratio, through characteristic velocity efficiency. It is found to be similar in both injection configurations when the chamber is very long. However, in a shorter combustion chamber, the triplet injector proves to be more efficient than the doublet injector despite a reduced residence time. Consequently, this triplet injector configuration offers a better mixing and spray combustion in the conditions of this study.

## Acknowledgments

The authors thank Nikhil Johnson and Alain Claverie for their outstanding contribution to this work, and wish to acknowledge the support of CNES Launchers Directorate.

## References

[1] B.L. Austin, S.D. Heister, W.E. Anderson, 2005. Characterization of pintle engine performance for nontoxic hypergolic bipropellants, *J. Propulsion Power* 21 : 627–635.

[2] Kang, H., Jang, D., Kwon, S., 2016. Demonstration of 500 N scale bipropellant thruster using non-toxic hypergolic fuel and hydrogen peroxide., *Aerospace Sci. Technology* 49: 209–214

[3] T. Zhang, Y. Cong, T. Li, J. Sun, X. Wang, L. Ma, D. Liang, L. Lin, 2004. Propulsive performance of hypergolic H202/kerosene bipropellant. J. Propulsion Power 20: 83–86.

[4] Brikner, N. , Protz, J., 2011. Modeling of the decomposition and combustion of hydrogen peroxide and ethanol for design of a bipropellant microrocket engine. Joint Propulsion Conference 2011-5851. AIAA.

[5] Jo, S., An, S., Kim, J., Yoon, H., Kwon, S., 2011. Performance characteristics of hydrogen peroxide/kerosene staged-bipropellant engine with axial fuel injector. J. Propulsion Power. 27: 684–691.

[6] Woschnak, A., Krejci, D., Schiebl, M., Scharlemann, C., 2013. Development of a green bipropellant hydrogen peroxide thruster for attitude control on satellites. Progress Propulsion Physics 4: 689–706.

[7] C. Indiana, B. Boust, M. Bellenoue, 2015. Ignition of sprays from impinging jets of green propellants: ethyl alcohol and hydrogen peroxide. European Combustion Meeting. The Combustion Institute.

[8] C. Indiana, B. Boust, M. Bellenoue, S. Petitot, 2016. Experimental combustion investigations from like-impingement sprays of green propellants. Joint Propulsion Conference 2016–4692. AIAA.

[9] S. Gordon, B.J. McBride, 1994. Computer program for calculation of complex chemical equilibrium compositions and applications”. NASA Reference Publication 1311.

[10] C. Indiana, M. Bellenoue, B. Boust, 2015. Experimental investigations of drop size distributions with impinging liquid jets using phase-Doppler anemometer. *Int. J. Energetic Materials Chemical Propulsion*. 14: 241–264.

[11] B. Boust, Q. Michalski, A. Claverie, C. Indiana, M. Bellenoue, 2017. Characterization of liquid impinging jet injector sprays for bi-propellant space propulsion: comparison of PDI and high-magnification shadowgraphy. $28^{th}$ Conference on Liquid Atomization and Spray Systems, ILASS–Europe 2017 (to be published).