DOI: 10.13009/EUCASS2019-279

8TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Atomization and combustion of a single unlike-triplet spray of storable bipropellants: hydrogen peroxide with ethanol or alkanes

N. Riaud, B. Boust* and M. Bellenoue**

* *PPrime Institute, CNRS – ISAE-ENSMA – University of Poitiers, Chasseneuil-du-Poitou, France*

nicolas.riaud@ensma.fr

Abstract

The present study focuses on the atomization and combustion of sprays generated by an unlike triplet injector, using hydrogen peroxide as oxidizer in association with ethanol or alkanes as fuels. Two injectors are tailored specifically for the fuels for a total flowrate of 10 g/s. The combustion chamber allows shadowgraphy and chemiluminescence visualizations. A characterization of the spray is performed in both reactive and inert conditions using high-magnification shadowgraphy. The performances are compared at steady-state in terms of characteristic velocity efficiency within a range of equivalence ratio 0.5–2.0 and pressure 3–6 bar.

Nomenclature

A	Area, m²		*Greek symbols*
c^*	Characteristic velocity, m/s	γ	Heat capacity ratio
Cd	Discharge coefficient	ΔP	Pressure difference between the tank and the chamber, Pa
d	Orifice diameter of the injector, m	η	Efficiency
HTP875	High Test Peroxide at 87.5% by weight	ρ	Fluid density, kg/m3
$\dot{m}$	Mass flow rate, kg/s	σ	Surface tension, N/m2
M	Molar mass, kg/mol	ER	Equivalence ratio
MR	Mixture ratio		*Subscripts*
OFO	Oxidizer fuel oxidizer triplet	cc	Combustion chamber
P	Pressure, Pa	F	Fuel
R	Ideal gas constant, J/mol/K	id	Ideal value for equilibrium state
T	Temperature, K	Ox	Oxidizer
V	Velocity, m/s	st	Stoichiometric
		t	Throat
		tot	Total

A nomenclature is introduced to refer to reactive tests according to the following:

	Injector	Fuel	Nozzle type	Nozzle throat diameter	Equivalence ratio
TC10ISO5	**T**riplet OFO	n-decane (n**C10**H22)	**ISO**	**5** mm	**-**
TC2ISO7-ER0.98	**T**riplet OFO	ethanol (**C2**H5OH)	**ISO**	**7** mm	**0.98**

DOI: 10.13009/EUCASS2019-279

1. Objectives

Space propulsion has made many innovations in its history from the time of space race to more recent times of the conquest of the space market. Still many efforts are paid to produce simple, cheap and over all reliable launchers systems. Recent successes have proven right the idea of reusability, still is the need for "green" storable propellants for the future. Such products require special considerations for the design of thrusters' engines, and their combustion performances and stability are to be demonstrated.

This study focuses on the injection and combustion of such "green" propellants, particularly hydrogen peroxide as the oxidizer and ethanol or alkanes as the respective fuels. The injection and atomization of propellants is provided by impingement of liquid jets in "unlike" triplet configuration. Hard work in the 60's US programs produced many results about the both "like" and "unlike" configurations. Authors highlighted key mechanisms in the process of atomization or mixing [1][2]. Recent simulations are now able to model accurately the phenomenon for doublet [3]. On the other hand, "unlike" triplet leads to higher efficiency as evidenced in previous studies [4][5].

ACSEL test bench has been developed for investigating the propellants and sprays in engine-like conditions, but for moderate mass flow rates (10 g/s) and chamber pressure (6 barA). HTP875 Propulse is used as the oxidizer in association with pure one-component fuel (ethanol or n-decane). The combustion chamber of 105-mm long by 60 mm diameter is equipped with two quartz windows for fast visualization; pressure and wall temperature are measured. The combustion is sustained for 6 seconds.

The specific objectives of this work are to investigate the atomization and combustion processes. Atomization will be characterized in inert and reactive conditions by high magnification shadowgraphy, which provides both visualization of the spray structure and droplet sizing. Combustion performance will be determined through the characteristic velocity efficiency during the steady state regime.

2. Experimental setups and methods

2.1. Definition of the injectors and liquids of interest

In this study, one type of injection qualified as "unlike triplet" is investigated for reactive and non-reactive fluids. The injector consists of two "oxidizer" liquid jets impinging with a single "fuel" liquid jet, as depicted in Figure 1. Two different injectors are used: OFO-etoh for ethanol and OFO-alk for alkanes. HTP is injected by two jets of 0.30 mm in diameter with a total angle of 60° (see Table 1). Concerning the fuel, the injectors are tailored for the propellants combination according to the stoichiometric mixture ratio (fuel diameter of 0.30 mm for the ethanol fuel orifice and 0.20 mm for the alkanes). Their characteristics are defined in Table 1. Due to the geometry of each injector and especially to the difficulty in manufacturing impinging-jet injectors, each spray deserves a specific characterization. The atomization quality is validated by visualization and the discharge coefficient is measured experimentally.

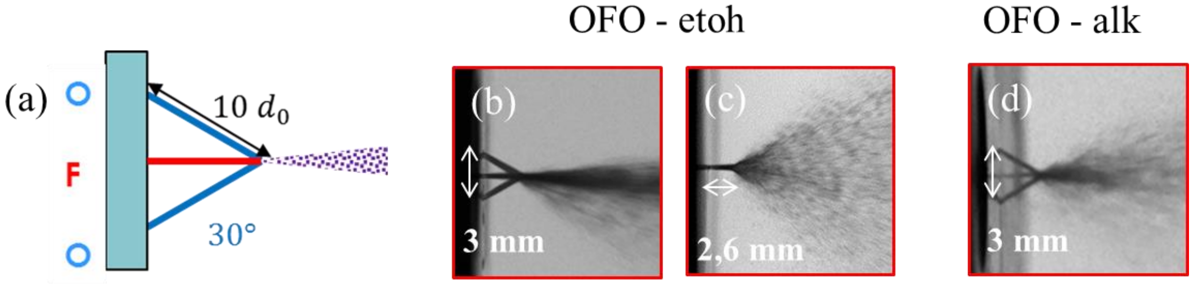


Figure 1: (a) OFO unlike triplet configuration; Shadowgraphy visualization (b) at 0°and (c) at 90° of the OFO-etoh injector (dOx = dF = 0.30 mm) spray of miscible ethanol and HTP875, and (d) at 0° of the OFO-alk injector (dOx = 0.30 mm, dF = 0.20 mm) spray of non-miscible HTP875 and n-decane.

DOI: 10.13009/EUCASS2019-279

Table 1 : Injectors geometry and characteristics

Injector	OFO-etoh		OFO-alk	
Liquid jet	Ox	F	Ox	F
Jet diameter (mm)	0.30	0.30	0.30	0.20
Angle between jets (°)	30	30	30	30
L/d before impingement	10	8.7	10	13
Discharge coefficient Cd	0.62	0.66	0.72	0.69
Liquids	HTP875	ethanol	HTP875	n-decane

In the present study, propellants are injected in the liquid state. Spray regime is usually considered in terms of dimensionless numbers governing the physics of the atomization process: the Reynolds (Re) and Weber (We) numbers (see equations 1-2). These numbers are calculated from the liquid properties, given in Table 2.

$$Re = \frac{\rho\, V\, d}{\mu} \qquad\qquad We = \frac{\rho\, V^2\, d}{\sigma} \qquad (1\text{-}2)$$

Where V is the liquid jet velocity, d is the diameter of the liquid jet (diameter of the injector orifice), μ is the dynamic viscosity, and σ is the surface tension.

Table 2 : Liquid properties at atmospheric conditions (P = 1 atm, T = 20°C), vapour pressure and heat of reaction

Liquid	**Viscosity [mPa s]**	**Density [kg/m3]**	**Surface tension [mN/m]**	**Vapor pressure (mbar) at 120°C**	**Heat of reaction with HTP875 (MJ/kg)**
n-decane	0.9	730	24	202	5.663
ethanol	1.2	790	23	4325	5.463
HTP875	1.9	1376	79	492	-
water	1.0	998	73	1980	-

Due to the respective mass flow rates targeted in reactive conditions, the typical injection pressures are 6 bar for ethanol, 11 bar for n-decane and 19 - 26 bar for HTP875. From these conditions, Reynolds and Weber numbers are calculated according to the incompressible Bernoulli flow equation and from atmospheric conditions (20°C, 1 atm), see Table 3.

Table 3 : Liquid jet velocity, Reynolds and Weber numbers of the liquid jets for the OFO-alk and OFO-etoh.

		Velocity (m/s)		**Re**		**We**	
		11 bar	**26 bar**	**11 barG**	**26 bar**	**11 bar**	**26 bar**
OFO-alk	**Water**		44.8		1.34E+04		8.23+03
	HTP875		38.1		8.31E+03		7.57E+03
	n-decane	36.2		5.79E+03		8.06E+03	
		6 bar	**19 bar**	**6 barG**	**19 bar**	**6 bar**	**19 bar**
OFO-etoh	**HTP875**		37.9		8.21E+04		7.46E+03
	ethanol	27.0		5.34E+03		7.47E+03	

2.2. ACSEL test bench

ACSEL test bench is dedicated to the study of liquid propellants combustion in an optical chamber (see Figure 2). The chamber is 105-mm long with an internal diameter of 60 mm. Propellants are injected under neutral gas pressurization regulated thanks to controllers mounted on the tanks. Two injector plates are used (Table 1), both including a single OFO triplet injector, a hydrogen-air torch (fed respectively at 4 barG) and a nitrogen purge (for safety sake). Half of the chamber height is visible through two parallel quartz windows. A normalized nozzle (ISO) is set at the exit of the combustion chamber with a critical diameter of either 5 or 7 mm.

DOI: 10.13009/EUCASS2019-279

ACSEL test bench is equipped with sensors for measurements of the respective tanks pressures (piezoresistive, precision 0.25%), fuel line pressure (Drück UNIK5000, precision 0.1%), mass flows (Bronkhorst Coriolis flowmeter models M15 for the oxidizer and M14 for the fuel, precision 0.2%), combustion chamber static pressure (Drück UNIK5000, precision 0.2%) anddynamic pressure (Kistler 601A, bandwidth 150 kHz, precision 0.5%), and wall temperatures (type K and Nanmac abrasive junction thermocouples).

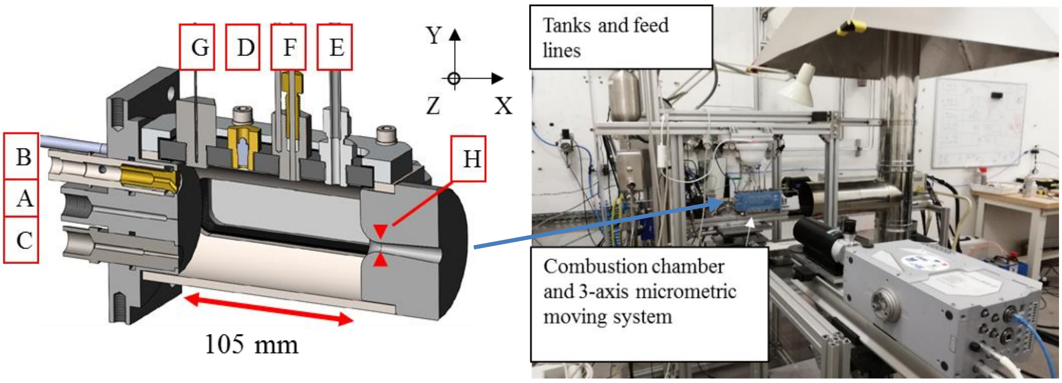


Figure 2 : ACSEL combustion chamber. (A) OFO-alk or OFO-etoh injector, (B) torch, (C) purge, (D) dynamic pressure, (E) static pressure, (F) wall thermocouples, (G) wall thermocouple, (H) nozzle throat diameter.

2.3. Optical diagnostics

Direct visualization and shadowgraphy are used to investigate multiple phenomena. A LED plate (Buechner HILIGHT 6/II) is used as a light source in strobe mode synchronised with a Photron mini AX-200 fast camera, using a controller (IPSC1 Buechner Photon Lines). Such mode enables recording the spray of one in two frames combined with the direct visualization of the flame.

Besides, droplets size and velocity are valuable for prediction of evaporation time and modelling of such process. A second method called HMS (“High Magnification Shadowgraphy”) developed by Boust et. al [6] is used to observe liquid structures with a high magnification. A Nd:YaG laser is used as the light source synchronised with a fast camera Photron SA-Z. This enables visualization at high speed (10 kHz, double frame) and high spatial resolution (7.2 µm/pixel). LaVision system and DaVis software are used for control and acquisition. Further features of the method are given in Table 4. The setup can be seen on Figure 3.

Table 4 : Features of the HMS technique and settings of the DaVis software

Acquisition rate	10 kHz	Image size	1024 x 1024 pixels
Exposure time	≈ 125 ns	Depth of field	3 mm
Interframe	4 µs	Spatial resolution	7.2 µm/pixel
Normalization radius	75 pixel	Minimum shadow area	5 pixel
Reduce pixel noise	Weak	Minimum slope	20 %
Binarization threshold	50 %	Ellipticity threshold	0.875
Velocity range Vy	-10 to 10 m/s	Velocity range Vx	10 to 90 m/s

DOI: 10.13009/EUCASS2019-279

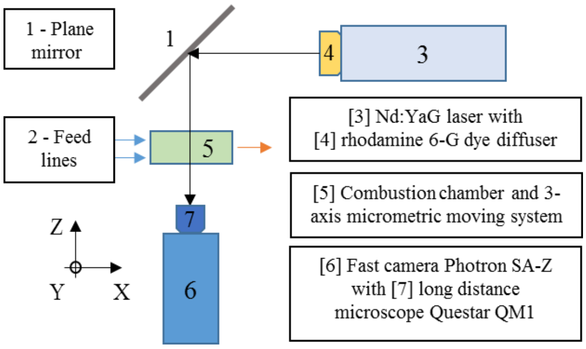


Figure 3 : Setup of the HMS on the ACSEL test bench.

In comparison to usual droplet sizing methods, HMS technique captures all the liquid structures in the spray, regardless of their geometry. This allows to investigate the whole process of atomization. The method is not dependent on the refractive index of the droplets. This is particularly relevant for mixed spray as the one generated by an OFO injector. However, droplets cannot be classified according to their fuel content. The sizing is still limited by a relatively low spatial resolution. Only objects with a size higher than two pixels (around 15 µm) can be visualized. As a result, diameter size distributions are filtered for the small droplets.

Direct visualization of the spontaneous chemiluminescence of the flame is recorded by the fast camera in strobe mode. Such images enable a tracking of both the liquid and gas phase during the combustion process.

2.4. Performance analysis

The characteristic velocity efficiency is calculated as an indicator of combustion performance of the propellants in the actual experimental conditions. Due to the response time of the flowmeters (0.2 s), the mass flows are re-evaluated using the Cd measurements as described in [5]. Experimental and theoretical characteristic velocity are calculated from the measurement of the injected mixture equivalence ratio (see equations (3-4)), the absolute chamber pressure, the total mass flow rate and the nozzle throat diameter (equations (5-7)).

$$\Phi = MR_{st}\frac{\dot{m}_F}{\dot{m}_{Ox}} \qquad MR_{st} = \left(\frac{\dot{m}_{Ox}}{\dot{m}_F}\right)_{st} \tag{3-4}$$

$$\eta_{c^*} = \frac{c^*_{exp}}{c^*_{id}} \qquad c^*_{exp} = \frac{P_{CC}\,A_t}{\dot{m}_{tot}} \qquad c^*_{id} = \frac{1}{Cd_t}\sqrt{\frac{R\,T_{id}}{\gamma_{id}\,M_{id}}}\left(\frac{2}{\gamma_{id}+1}\right)^{-\frac{1\gamma_{id}+1}{2\gamma_{id}-1}} \tag{5-7}$$

3. Experimental results

In this section, the spray is characterized either in reactive or inert conditions. The effect of the heat release on the spray is highlighted from HMS measurements: droplets size, number, velocity. The structure of the flame and its anchoring on the spray are also discussed from the combined direct visualization with the shadowgraphy. The performance results are discussed for the two tested fuels with two different nozzles.

3.1. Sprays characteristics

The HMS technique offers an insight view of the impingement process from the liquid sheet to various structures and ligaments. Multiple levels of breakups are observed in short distance from the impingement.

Tests in reactive conditions are also performed in order to get a direct measurement of the droplet size and velocity in the combustion chamber. N-decane is injected at stoichiometric conditions using the OFO-alk injector. A comparison is done with non-reactive combination at atmospheric conditions and in the same conditions of injection pressure using water in place of the “oxidizer” for safety reasons. In this case, the chamber is heated up to 90 to 110°C to avoid the

DOI: 10.13009/EUCASS2019-279

production of a liquid film on the windows. The nozzle is removed to avoid liquid accumulation in the chamber. Visualizations are performed at distance x = 0–100 mm from the impinging zone (Figure 4). Sprays are diagnosed in permanent conditions according to the injection and combustion processes.

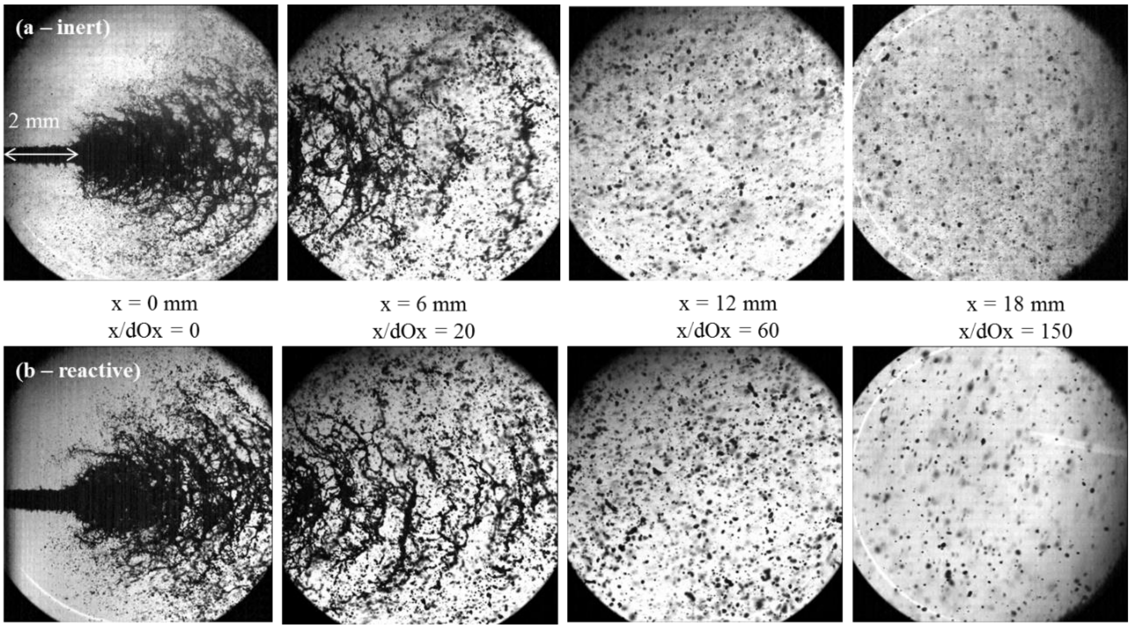


Figure 4 : HMS images of (a) n-decane/water, and (b) n-decane/HTP875 spray ($P_{CC} = 3\ barA$ (ISO7), $\Phi = 1.00$). $\Delta P_{Ox} = 26\ barG$; $\Delta P_F = 11\ barG$, OFO-alk injector (dOx = 0.30 mm, dF = 0.20 mm).

The determination of droplets size is done using the DaVis software – ParticleMasterShadow mode. The setting of the software is described in Table 4. Average diameters are calculated out of more than 100,000 droplets detected. Statistics are determined from the distribution with a correction with the diameter size according to the detectability (defined as a “statistical weight” in DaVis [7]). Besides, a criterion on the ellipticity is set to avoid superimposed structures on the image.
Authors would like to emphasize that the values of statistical diameters are overestimated because of the relatively low resolution of the method, as discussed in section 2.3. Only droplets over the detectability of 2 pixels (15 µm) can be measured. One should note that only droplets moving in the depth of field can be measured, so that the velocity is only in the XY-plane of the spray.

Two tests in non-reactive and reactive cases have been taken out to illustrate the effect of the combustion heat release on the spray characteristics. A selected range of image is taken within steady time periods for the same duration (400 ms), with respectively 265,000 and 972,500 detected droplets. The distance from the impingement point is x = 62 mm, which is located inside the flame area at stoichiometry equivalence ratio. Compared to the inert case, the reactive case exhibits a faster evaporation of the smallest droplets, which can be observed from their respective number, and from their respective distributions of droplets size and velocity (see Figure 5).

From Figure 5-a, the diameters distribution exhibit a significant decrease of the number of small droplets from inert to reactive conditions. This highlights the effect of the combustion heat release on the spray, as seen also in Table 5 in terms of data rate (number of droplets detected per image) that decreases faster. Because the smallest ones are evaporated (or they are under the detection limit), a higher number of large droplets is measured relatively to the whole statistics of detected droplets which leads to higher average diameters (D10 and D32 in Table 5). Figure 5-b deals with the measurement of the droplets velocity. Velocity ranges are reduced from inert to reactive conditions which may be due to the chamber pressure and high aerodynamic conditions in the combustion chamber. Besides, small droplets with lower velocity have disappeared (see the diameter-velocity chart Figure 5-c), resulting in more homogeneous distribution of velocity.

DOI: 10.13009/EUCASS2019-279

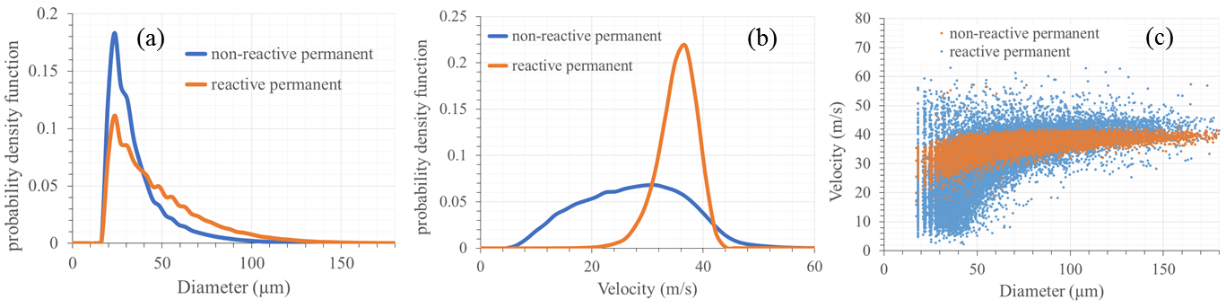


Figure 5 : Comparison of two tests of n-decane/water spray (t=3.12-3.52 s) and n-decane/HTP875 ($P_{CC} = 3\ barA$ (ISO7), $\Phi = 1.00$, t =4.35-4.75 s). $\Delta P_{Ox} = 26\ barG$; $\Delta P_F = 11\ barG$, OFO-alk injector (dOx = 0.30 mm, dF = 0.20 mm).

Investigating the droplets characteristics from the impingement point up to 68 mm (x/dOx = 206), the average size of the detected droplets is reported in Table 5 in terms of mean diameter, Sauter diameter, and data rate. As discussed, the increase in diameter size with the x-distance is the consequence of the significant decrease in the number of small droplets relatively to the large ones. This drives to a constant average diameter relatively to the distance and must be considered in the analysis. Besides, the data rate (number of droplets measured per image) drops with the distance, for both inert and reactive conditions. The first reason is that the spray has a diverging angle so that the liquid mass flow in a constant probe volume is reduced with a rate inversely proportional to the x-distance. Secondly, evaporation applies so only the bigger droplets remain.. Finally, for the same processing settings, the detectability is a function of the backlight and contrast. As a result, the detectability of the inert spray is lower than for the reactive one because of its higher density; the flame radiation also changes the light. A bias effect must also be taken into account for inert tests at short x-distance because the heating was not enough to avoid the formation of a liquid film on the window, which changed dramatically the detection.

Table 5 : Average diameter, Sauter diameter, and data rate of detected droplets relatively to the axial distance from the impingement point for reactive and non-reactive tests.

	D10 (µm)		D32 (µm)		data rate (number/image)	
x (mm)	Reactive	Non-reactive	Reactive	Non-reactive	Reactive	Non-reactive
0	37	40	69	88	315	447
6	45	51	142	177	760	371
12	52	53	141	130	916	596
18	52	47	108	88	677	418
24	52		97		434	
44	47	38	79	68	121	223
56	47	38	78	65	101	186
62	47	35	77	59	86	247

3.2. Combustion performances at stabilised regime

3.2.1. Operating conditions

A typical sequence is shown in Figure 6. Prior to the test, the chamber is preheated up to 130°C. One second of combined liquid propellant injection and torch operation is set for the ignition to happen and to reach sustained and stable combustion. At t = 4 s, the torch is cut off and the injection continues for 5 s in sustained combustion regime.

Four different cases, based on propellants combinations or nozzle throat diameter, are tested (see corresponding values for the stoichiometric mixture in Table 6). Performances are assessed over a range of injected equivalence ratio from around 0.5 to 2.0. Tests with ethanol are performed at constant total mass flow rate, whereas tests with n-decane are

DOI: 10.13009/EUCASS2019-279

carried out at constant oxidizer pressure of 30 barG. The first permits to work at same residence time, while the second is assumed to produce almost constant oxidizer droplets size distribution.

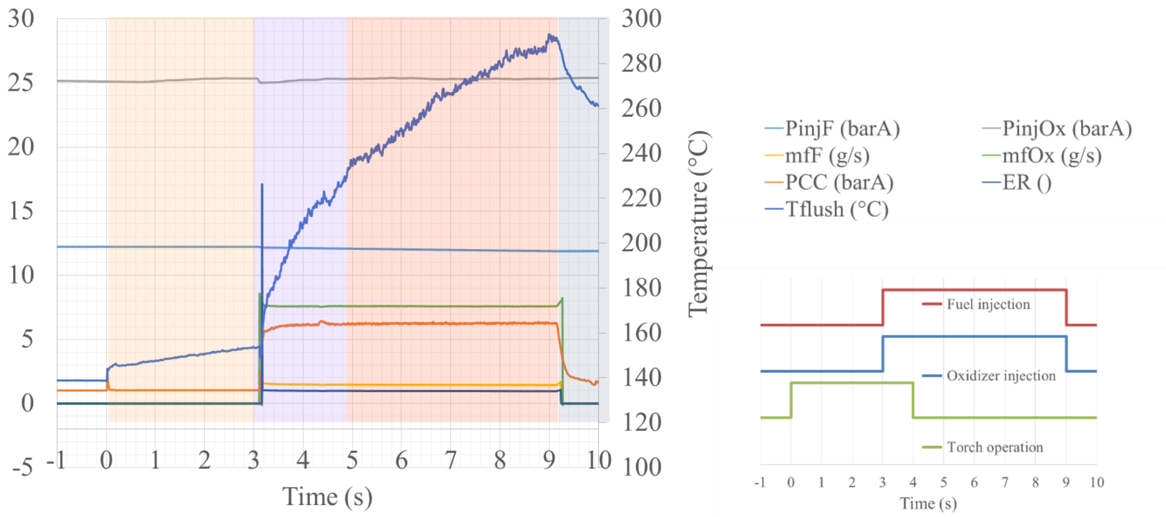


Figure 6 : Time chart of a reactive test (ethanol/HTP875, $P_{CC} = 6\ barA$ (ISO5), $\Phi = 0.98$, OFO-etoh (dOx = dF = 0.30 mm).

Nomenclature	Fuel	Injector	Nozzle throat diameter	ΔP_F bar	ΔP_{Ox} bar	P_{CC} barA	$\dot{m}_{tot}$ g/s	Φ
C2ISO5	ethanol	OFO-etoh	5 mm	5.75	19.09	6.24	9.04	0.98
C2ISO7	ethanol	OFO-etoh	7 mm	5.42	20.16	3.23	9.14	0.95
C10ISO5	n-decane	OFO-alk	5 mm	11.05	24.26	5.73	8.09	0.94
C10ISO7	n-decane	OFO-alk	7 mm	11.59	27.52	2.98	8.22	0.96

Table 6 : Operating conditions for the selected fuels at near-stoichiometry. Average values calculated at steady regime for a single representative test.

3.2.2. Visualization of the flame in steady regime

Averaged visualizations of the spray and the flame are presented on Figure 7 for each of the four tests presented in Table 6 within the steady period considered for the performance analysis. First, the two sprays, respectively ethanol/HTP875 from the OFO-etoh injector and n-decane/HTP875 from the OFO-alk injector, have similar aspects: both deviate toward the bottom of the chamber.
In near-stoichiometric conditions, the holding of the flame differs for each test with respect to the nozzle configuration and fuel. For a 5-mm diameter nozzle, the n-decane/HTP875 flame is shortened and more luminous in comparison with the ethanol one. This is mainly due to the presence of soot. Note that the aperture of the camera has been adapted to avoid the saturation of the CCD sensor. For the 7-mm nozzle diameter, the same behaviour is observed although the flame does not propagate into the whole chamber; flame lift-off appears.

DOI: 10.13009/EUCASS2019-279

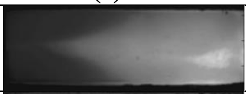
Propellants	ethanol / HTP875		n-decane / HTP875	
Nozzle	(a) ISO5	(b) ISO7	(c) ISO5	(d) ISO7
Flame				
Spray				

Figure 7 : Average images of the flame and sprays at near-stoichiometric conditions. (a) C2ISO5-ER0.98 and (b) C2ISO7-ER0.95. OFO-etoh (dOx = dF = 0.30 mm). Exp. = 25 µs, aperture « O » (c) C10ISO5-ER0.94 and (d) C10ISO7-ER0.96. OFO-alk (dOx = 0.30 mm, dF = 0.20 mm). Exp. = 25 µs, aperture « M ».

3.2.3. Performances

For each of the four conditions, a variation of equivalence ratio was carried out at least twice at two different times. Tests were performed in increasing and decreasing order of the equivalence ratio. Results of the four tested configurations are summarised in Figure 8.

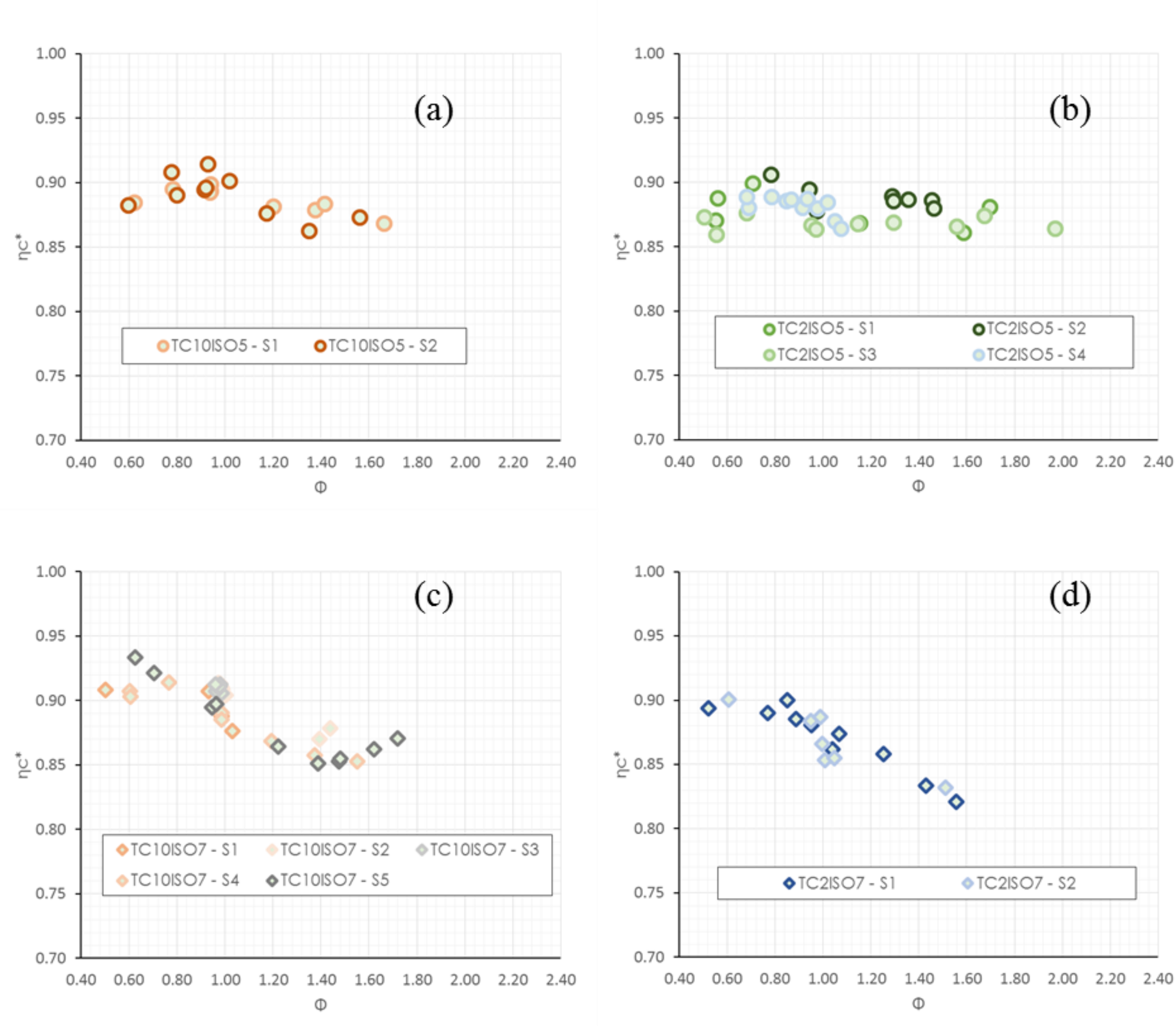


Figure 8 : Characteristic velocity efficiency of tests at ISO5 with (a) n-decane, (b) ethanol, and ISO7 with (c) n-decane, (d) ethanol.

DOI: 10.13009/EUCASS2019-279

From Figure 8, one will notice a low dispersion between points, with no more than $\pm$ 3% at stoichiometry in the case of the n-decane tests with a nozzle throat diameter of 7 mm (c). Higher efficiency has been obtained with n-decane respectively to ethanol (Table 7). With the 5-mm throat diameter nozzle, the efficiency is almost constant over the range of equivalence ratio. The residence time is long enough to vaporize and for the chemical kinetics to burn most of the propellants flow rate. The characteristic velocity efficiency may be limited by the heat losses to the walls.

Table 7 : Characteristic velocity efficiency at near-stoichiometric conditions (ER = 0.9 to 1.1). Average $\pm$ standard deviation

Fuel / Nozzle throat diameter	ethanol	n-decane
5 mm	0.88 ± 0.010	0.90 ± 0.007
7 mm	0.87 ± 0.013	0.90 ± 0.010

In the case of the 7-mm nozzle, the residence time is half that of 5-mm nozzle which may also limit the reaction progress. As a result, a lift-off is observed: the average flame position gets closer to the exit nozzle as observed on Figure 9. Furthermore, a significant decrease of the efficiency is observed in fuel-rich conditions for the two propellants combinations, mainly with the 7-mm nozzle (Figure 8-(c,d)). This result has been observed in a previous study [4], even though in the presented tests the oxidizer injection pressure is constant, so that the oxidizer droplets size is assumed to be independent of the ER..

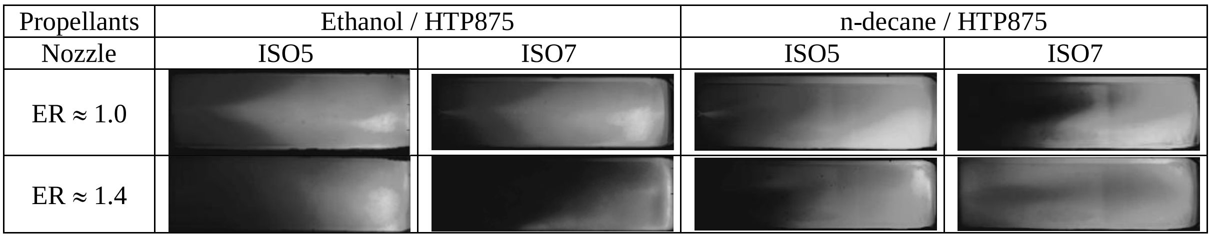


Figure 9 : Average images of the flame at stoichiometric and fuel-rich conditions. (a) C2ISO5-ER0.98, (b) C2ISO7-ER0.95, (c) C2ISO5-ER1.46 and (d) C2ISO7-ER1.43. OFO-etoh (dOx = dF = 0.30 mm). Exp. = 25 µs, resp. aperture "O", "O", "N" and "O". (e) C10ISO5-ER0.94 and (f) C10ISO7-ER0.96, (g) C10ISO5-ER1.42 and (h) C10ISO7-ER1.39. OFO-alk (dOx = 0.30 mm, dF = 0.20 mm). Exp. = 25 µs, resp. aperture « M », "M", "G" and "L".

4. Conclusion

Original visualizations of the spray generated by unlike triplet injectors have been obtained using high-magnification shadowgraphy in reactive conditions, relevant to storable bipropellant combustion. Compared to the inert case, the number of droplets is dramatically reduced in the reactive case due to the effect of the heat release of the flame, and the mean diameter is therefore increased. For instance, 200 diameters downstream of the impinging point, the mean droplet diameter is 47 µm for the reactive case (n-decane/HTP875) compared to 35 µm in the case of the inert conditions (n-decane/H_2O).

Simultaneous chemiluminescence visualizations combined with shadowgraphy allow in-situ investigation of the flame anchoring on the spray. Flame lift-off is found to occur in particular conditions, either for ethanol or n-decane: it is favored by a low chamber pressure and residence time, or by fuel-rich equivalence ratio. This effect is consistent with the measurement of the characteristic velocity efficiency that drops of a few percent in the fuel-rich domain. Nevertheless, in near-stoichiometric conditions such efficiency still reaches 90% for n-decane/HTP875, and 88% for ethanol/HTP875.

DOI: 10.13009/EUCASS2019-279

Acknowledgements

The authors would like to thank Alain CLAVERIE, Yann GUELOU, Emilie LABARTHE, and Jean-Baptiste LEBON. This work is supported by CNES.

References

[1] D. J. Ferrenberg, A., Hunt, K., “Atomization and mixing study,” 1985.
[2] R. W. Riebling, “Criteria for optimum propellant mixing in impinging-jet injection elements.,” *J. Spacecr. Rockets*, vol. 4, no. 6, pp. 817–819, 1967.
[3] X. Chen and V. Yang, “Recent advances in physical understanding and quantitative prediction of impinging-jet dynamics and atomization,” *Chinese J. Aeronaut.*, vol. 32, no. 1, pp. 45–57, 2019.
[4] Indiana, Boust, Azuma, and Bellenoue, “Effect of Injector Design on the Combustion of Ethanol and Hydrogen Peroxide Sprays,” *J. Propuls. Power*, 2019.
[5] N. Riaud, B. Boust, and M. Bellenoue, “Effect of fuel properties on the combustion of storable bipropellants: alkanes, ethanol with hydrogen peroxide,” *Int. J. Energ. Mater. Chem. Propuls.*, vol. 18, no. 2, pp. 111–131, 2019.
[6] B. Boust, Q. Michalski, A. Claverie, C. Indiana, and M. Bellenoue, “Characterization of Liquid Impinging Jet Injector Sprays for Bi-Propellant Space Propulsion: Comparison of PDI and High-Magnification Shadowgraphy,” no. September, pp. 6–8, 2017.
[7] LaVision GmbH, « Particle Master Shadow Manual for Davis 8.4», pp 51-56, 2017.