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PERGOLA: an experimental facility to investigate storable propellants' combustion

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Abstract

PPRIME Institute and CNES have initiated research activities to investigate the propulsion behaviour of liquid storable propellants, and the related phenomena: atomization of propellants, ignition ability, combustion stability, propulsion efficiency. For this purpose, a specific facility "PERGOLA" has been designed with high modularity, allowing physical diagnostics in a pressurized combustor featuring relevant flow conditions (a few hundred g/s, 5 MPa). The first results demonstrate the capability of PERGOLA facility and characterize the behaviour of a reference storable bipropellant system: ethanol and hydrogen peroxide. The overall combustion performance is also characterized in terms of stability, characteristic velocity and efficiency.

1 Introduction

This study focuses on green storable propellants for space thruster applications. Some advantages of such propellants are their easy handling, low environmental impact and intrinsic safety, among others. They also have to yield high specific impulse and ignition ability, to allow efficient propulsion and re-ignition capabilities.

In the literature, most studies dealing with bi-propellant storable propulsion are either based on hypergolic systems [1]-[3], or performed through staged combustion [4]-[6], i.e. with a preliminary decomposition of monopropellant on a catalyst yielding oxygen, before burning with the fuel in the combustion chamber.

Another solution for storable propulsion is to perform non-hypergolic, non-catalytic combustion. Storable fuel and oxidizer are injected in liquid phase, and burn in the combustion chamber without hypergolic properties nor catalytic decomposition, thus offering numerous possibilities for fuel choice, and preventing from the uncontrolled decomposition risk of the monopropellant. In this context, PPRIME Institute and CNES have initiated fundamental research to investigate the propulsion behaviour of liquid storable propellants in these conditions, as well as the related phenomena: atomization of propellants, ignition ability, combustion stability, propulsion efficiency. For this purpose, a specific facility "PERGOLA" has been designed with high modularity, allowing physical diagnostics in a pressurized combustor featuring relevant flow conditions. Although PERGOLA is not a full-scale thruster, it is a large facility allowing high combustion pressure and flowrate (a few hundred g/s) compared to our lab-scale facility ACSEL [7]-[8] that features lower capability (combustion at 0.5 MPa and a few tens g/s).

In this work, a green bipropellant system is investigated: ethanol and hydrogen peroxide. Based on these reference propellants, the objectives of the present study are: i) to demonstrate the ignition ability and combustion stability of liquid storable propellants, ii) to evaluate their combustion performance at engine-relevant conditions using large-scale PERGOLA facility.

2 Experiment and diagnostics

2.1 Infrastructure

The implementation of storable bipropellant combustion at large scale requires a specific environment to allow for the storage, handling and use of such propellants in safe conditions. For this, a dedicated infrastructure was designed and settled at PPRIME with the technical support of ISAE-ENSMA. PERGOLA was built in 2015, as part of the research platform PROMETEE under construction.

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PERGOLA research site offers a storage capability for liquid fuels and oxidizers, an experimental building and a separate control station. It allows to reach a propulsive thrust up to 1 kN, and a combustion pressure up to 5 MPa and a total propellant flow rate of a few hundred g/s under 8 MPa pressure. The maximum test duration is set to 1 mn. Overall, a Technology Readiness Level (TRL) of 4 is targeted.

To reach these conditions, PERGOLA facility involves several subsystems: the feeding system flows the propellants inside the combustor by inert gas pressurization (GN2), a GH2-air torch is used for ignition, and a propane-air post-combustion torch is used to secure propellants consumption in the case of misfire. Burned gases are diluted and exhausted by the ventilation system. A pressurized cooling system allows a good control of the combustor wall temperature.

As a result, the reactor is placed inside an adequate test cell equipped with a thrust bench, allowing at once the study of atomization, combustion and propulsion phenomena (see Figure 1). This provides a unique framework for research activities on storable propellants' combustion in engine-like conditions.

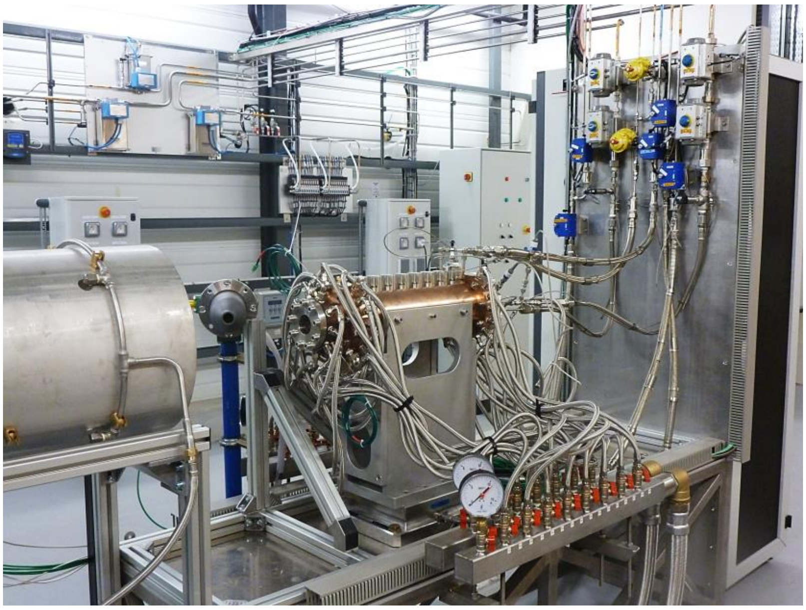

Figure 1: PERGOLA facility

2.2 Experimental setup

In this study, PERGOLA facility is operated with well-known storable propellants, for validation purposes. High-Test Peroxide (HTP) is used as an oxidizer, and ethanol as a fuel (see Table 1); taking into account the concentration of propellants, the stoichiometric mixture ratio MRst of this bipropellant system is 5.01. It is worth noting that 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

The combustor has a modular conception composed of an injection module, a combustion chamber and a throat (see Figure 2). The first experiments are carried out with an opaque combustion chamber, in order to secure the injection and ignition processes.

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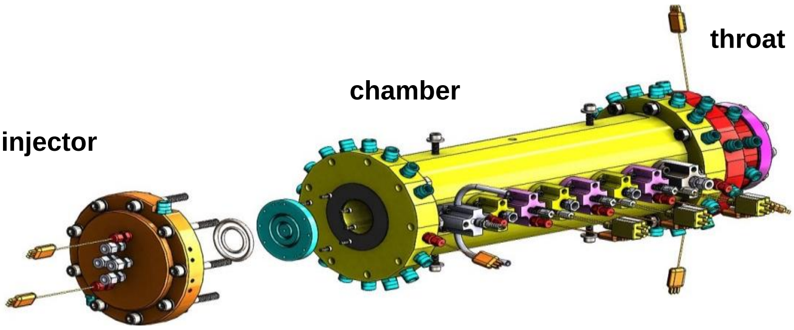

Figure 2: Mechanical assembly of the opaque combustor

The cylindrical combustion chamber is equipped with an ignition torch, sensors and a safety purge system (inert gas). All parts of the combustor are water-cooled to allow a good control of the initial conditions.

Ignition is a key issue in non-hypergolic bipropellant combustion. Indeed, most systems use a catalyst bed for this purpose, whereas non-catalyst systems usually burn at once the propellants while the torch is still firing at negligible power and flow rate [11]. On the contrary, in our study the GH2-air torch used for ignition is operated before the injection of propellants and during the early phase of propellants combustion. For the tests presented hereafter, its thermal power is quite elevated compared to the combustor thermal power (up to 30%), but it is stopped to perform measurements during the stabilized combustion phase. This way, there is no influence of the ignition device over the steady combustion results.

As both propellants are injected in liquid phase, injection is a crucial step of the process. It is performed by like-impinging jet injectors, which is favourable to the atomization quality. Like-doublets of each propellant are placed circumferentially on the injector plate (see Figure 3).

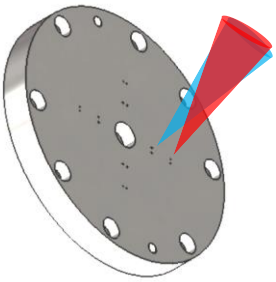

Figure 3: Injector plate illustrating the sprays of fuel (red) and oxidizer (blue)

The combustor can be used with several ejection nozzles of different throat section, leading to a variation in characteristic chamber length L* by 1:3.3. Characteristic chamber length L* depends on the combustion chamber volume V_{cc} and throat cross-section A_{throat}, see Eq. (1). In this study only convergent nozzles are used to study the combustion process. A deeper study focused on propulsion may require the use of divergent nozzles, particularly to improve the reactor thrust and assess the specific impulse.

$$L^* = \frac{V_{cc}}{A_{throat}} \tag{1}$$

2.3 Diagnostics

The facility is instrumented with sensors in order to quantify its behaviour with respect to injection (propellants pressure, mass flow rate and temperature), combustion (pressure in the combustion chamber, wall heat flux) and propulsion (thrust). The sensors bandwidth (see Table 2) is compatible with the unsteady processes at work in such a facility: ignition or combustion instabilities.

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Table 2: Instrumentation

	Principle	**Sensor**	**Range**	**Bandwidth**	**Uncertainty**
Data Acquisition Device	Synchronous	Astromed TMX	0-10V	100 kHz	16 bit
Propellant mass flow rate: Qfuel, Qox	Coriolis	Rheonik RHM08	–	–	0.5 %
Propellant pressure: Pfuel, Pox	Piezoresistive	HBM P8AP	10 MPa	60 kHz	0.3 %
Temperature	K Thermocouple		1000°C	–	1 K
Combustion pressure: Pcc	Piezoelectric	Kistler 6067C	25 MPa	90 kHz	0.3 %
Wall heat flux: Qw	Surface thermocouple	Nanmac TCK12-3	–	–	–
Thrust : Fx, Fy, Fz	Piezoelectric	Kistler 9255C	50 kN	2.2 kHz	0.5 %

The experimental measurements are carried out for the evaluation of combustion performance, especially the characteristic velocity c* and its efficiency η_{c^*} (see Eq. 2). The characteristic velocity depends on combustion pressure P_{cc}, throat cross-section A_{throat} and mass flowrate Q_{cc}. The prediction of theoretical burned gas properties is done using CEA computation code [9], e.g. burned gas temperature T_b and heat capacity ratio γ_b, leading to the theoretical characteristic velocity c^*_{th}.

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

3 Results and discussion

3.1 Injector characterization

Due to the liquid phase of propellants, water-cooled walls may favour the propellants deposit on the cold surface. Thus, the injector is designed to spray the propellants towards the combustion chamber centreline so as to prevent the wall wetting.

The injector is characterized with water so as to check the good flow rate and spraying in inert conditions (see Figure 4). The sprays of both propellants are well directed towards each other, and the discharge coefficients are evaluated.

The distribution of drop size and velocity is evaluated in a separate setup featuring the same impinging jet spraying process [10]. According to this study, the drop size distribution is characterized by a Sauter mean diameter as small as 10–20% of the injector hole diameter, depending of the fluid and pressure drop, which makes it an efficient way to produce fine sprays at moderate injection pressure.

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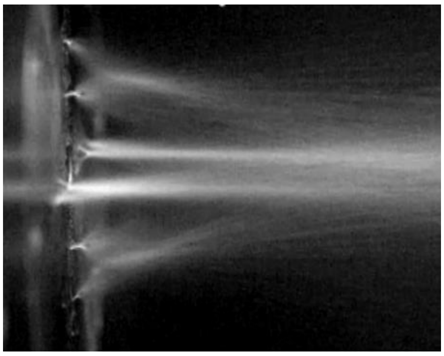

Figure 4: Water test of the injector

3.2 Overview of a typical firing test

A typical firing test is presented hereafter to illustrate the operation sequence of PERGOLA (see Figure 6). As safety relies on the control of the propellants' consumption and equivalence ratio, the facility is started at low mass flowrate, then from t = 5 s a ramp is performed to reach the target conditions, then the ignition torch is stopped. Relevant measurements are obtained in stabilized conditions from t = 11 s, i.e. when the facility operates in self-sustained combustion. The expected quantities of interest reach a plateau: fuel pressure Pfuel, oxidizer pressure Pox, mass flowrate Q, combustion pressure Pcc, equivalence ratio ER, thrust Fx.

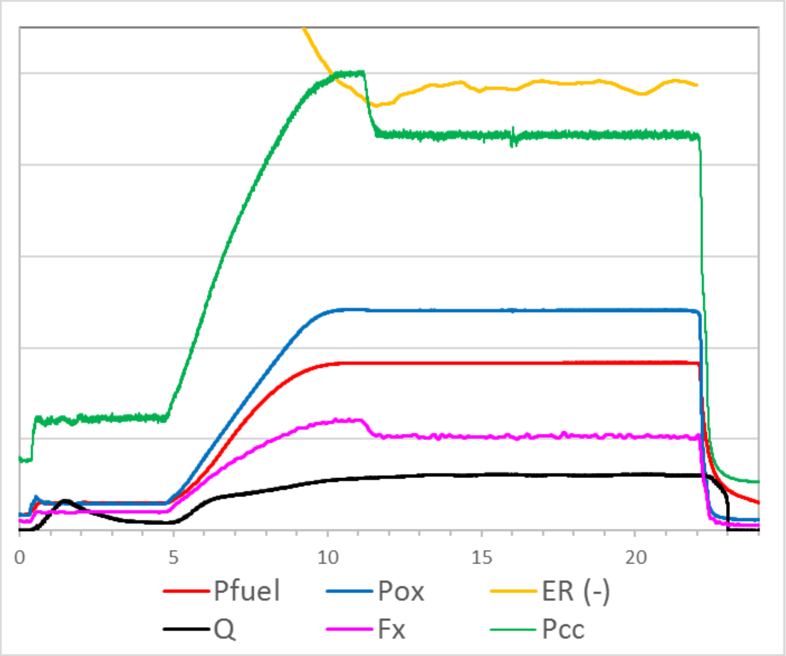

Figure 5: Measurements obtained during a firing test

The exhaust plume is characterized by direct visualization at the throat exit (see Figure 6). The flow exhibits a characteristic Mach disk structure of choked and under-expanded nozzle. The yellow color is caused mainly by the spontaneous emission of sodium inside the burned gas; this species is one of the stabilizing products of HTP.

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Figure 6: Visualization of the exhaust plume during a firing test with ignition torch firing (left) then stopped (right)

The thermal behaviour of the combustor is also investigated locally at a single point instrumented with a surface thermocouple (see Figure 7), and located along the combustion chamber at x/L = 0.85. The wall temperature increase during a firing test, ΔTw = Tw(t) – Tw(t=0), raises during the ramp and during the plateau of maximum mass flow rate, from t = 11 s. The corresponding wall heat flux, Qw, is quite stable during this phase, although local phenomena seem to affect its magnitude. For example, the end of ignition torch operation at t = 11 s modifies the flame structure due the end of hydrogen and radicals addition by the torch; this change in flame kinetics affects the flame length (as observed at the throat exit, see Figure 6) and the resulting flow temperature distribution. Hence this diagnostic is dependent on the local flow properties, e.g. burned gas temperature and velocity.

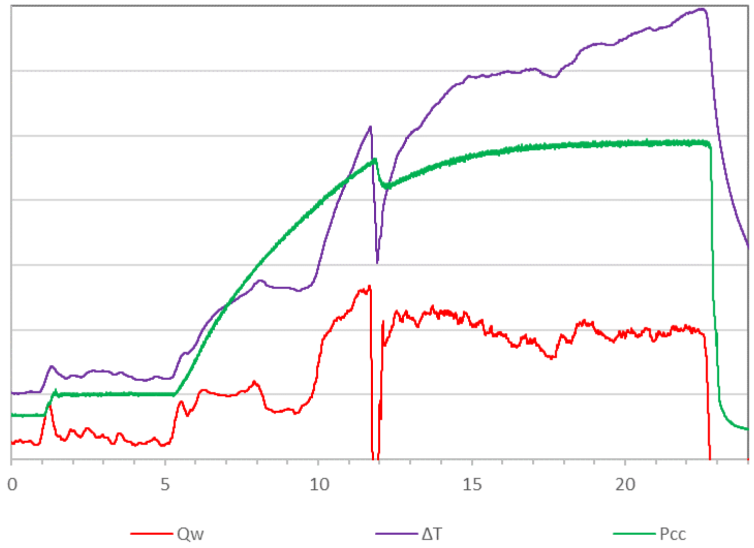

Figure 7: Wall heat flux and surface temperature measurements at x/L = 0.85

Time-resolved diagnostics are performed to check the stability of the investigated processes: injection, combustion and ejection flows. As for combustion, its stability is confirmed by the ratio of its rms and average values: Pcc'/Pcc < 6% in stabilized conditions. The power spectrum density (PSD) of axial thrust is also drawn from experiments (see Figure 8): it shows characteristic frequencies related to the processes of combustion and burned gas flow across the nozzle. High-speed visualization of the ejection flow is performed during the same test (see Figure 9): it confirms the instantaneous flow structure and its stability. Such dynamic instrumentation is a useful tool to determine the stability and unsteady behaviour of the overall propulsion process.

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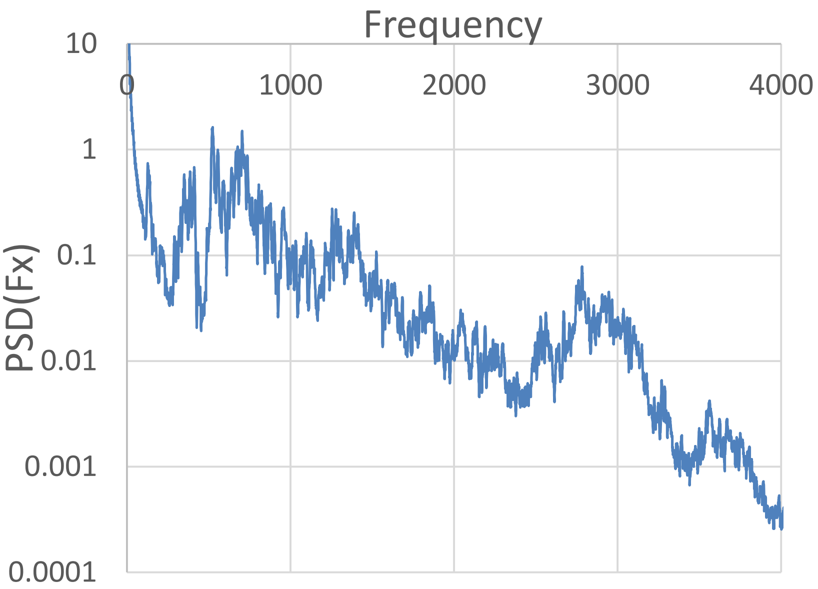

Figure 8: Power spectrum density of axial thrust during the stabilized combustion phase

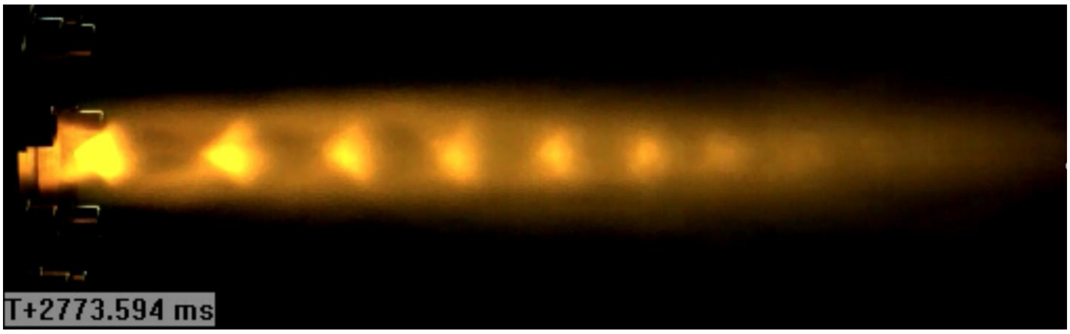

Figure 9: High-speed visualization at the throat during the stabilized combustion phase (Phantom v310, 12 bit, 3kHz)

3.3 Experimental results

The experimental conditions investigate a variation of mass flowrate by 1:1.5, of combustion pressure by 1:3, and of equivalence ratio. Measurements are averaged over the stabilized operation phase. The corresponding data report the evolution of combustion pressure Pcc and thrust Fx in these conditions (see Figure 10), for the three configurations of characteristic length L*. The results presented in the following will be normalized by a reference value denoted as "°", e.g. for characteristic length: L*/L*°.

The evolution of combustion pressure versus mass flow rate is almost linear, confirming the choked flow regime at the throat. The evolution of the ratio axial thrust to throat section is also linear versus combustion pressure, which is consistent with the use of convergent exit nozzles.

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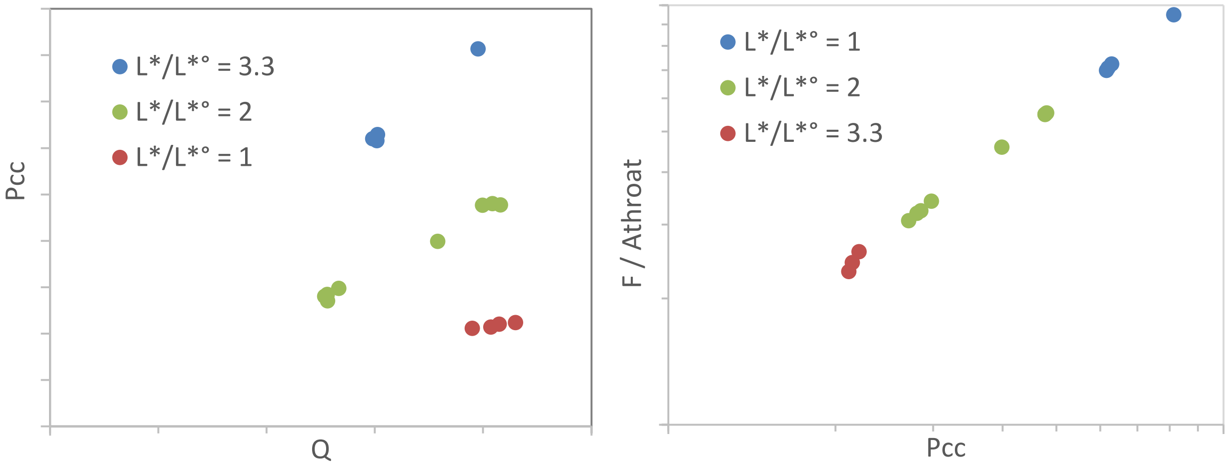

Figure 10: Evolution of combustion pressure (left), and thrust (right) in stabilized conditions

3.4 Performance analysis

The experimental results allow the evaluation of combustion performance, through the characteristic velocity c* and its efficiency ηc* (see Figure 11), as defined from Eq. (2). Along the conditions investigated in this study, c* reaches typical magnitudes of 1500 m/s, which corresponds to a typical efficiency ηc* of 0.90. Characteristic velocity efficiency ηc* follows a bell-shaped curve versus equivalence ratio with a maximum due to stoichiometry, which is a common result in chemical propulsion. It had been evidenced for the same propellants in our previous work at lab-scale [8], with reduced mass flow rate and pressure: the same behaviour was observed but ηc* was more elevated, reaching up to 0.87–0.97. However, efficiency ηc* does not depend only on equivalence ratio, but mainly on characteristic length L* that is linked to the residence time.

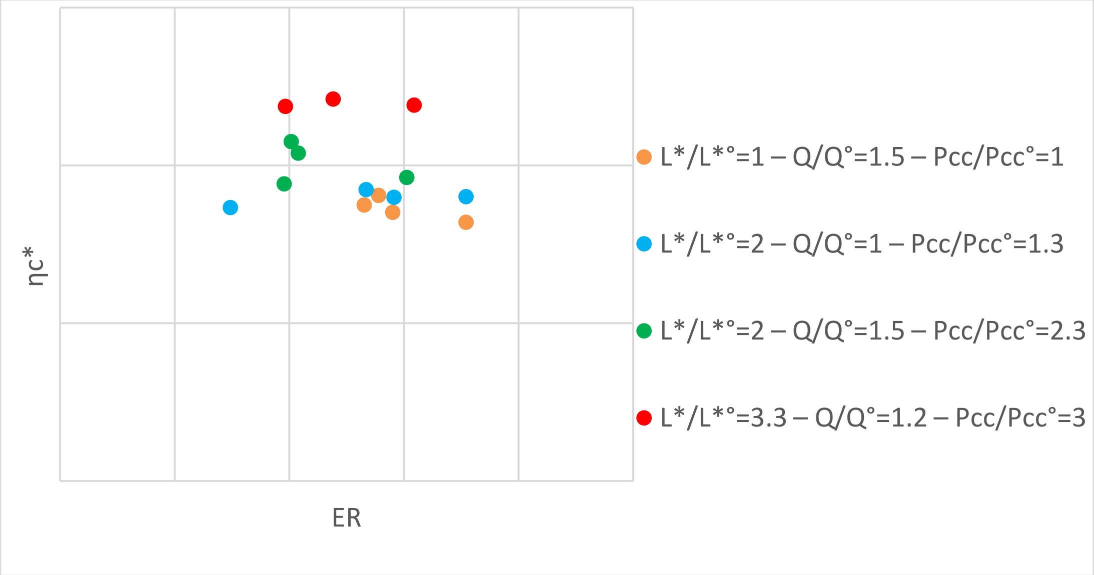

Figure 11: Evolution of characteristic velocity efficiency versus equivalence ratio

Indeed, the present data clearly reveal the effect of residence time over combustion efficiency (see Figure 12): as the characteristic length L* increases, combustion pressure Pcc increases, thus increasing the residence time inside the combustion chamber. A longer residence time allows a higher progress of the chemical reaction of combustion. This causes an increase in characteristic velocity efficiency ηc*, that is maximum at highest L* and Pcc conditions. The evolution of efficiency ηc* versus residence time is almost linear, as indicated by Figure 12.

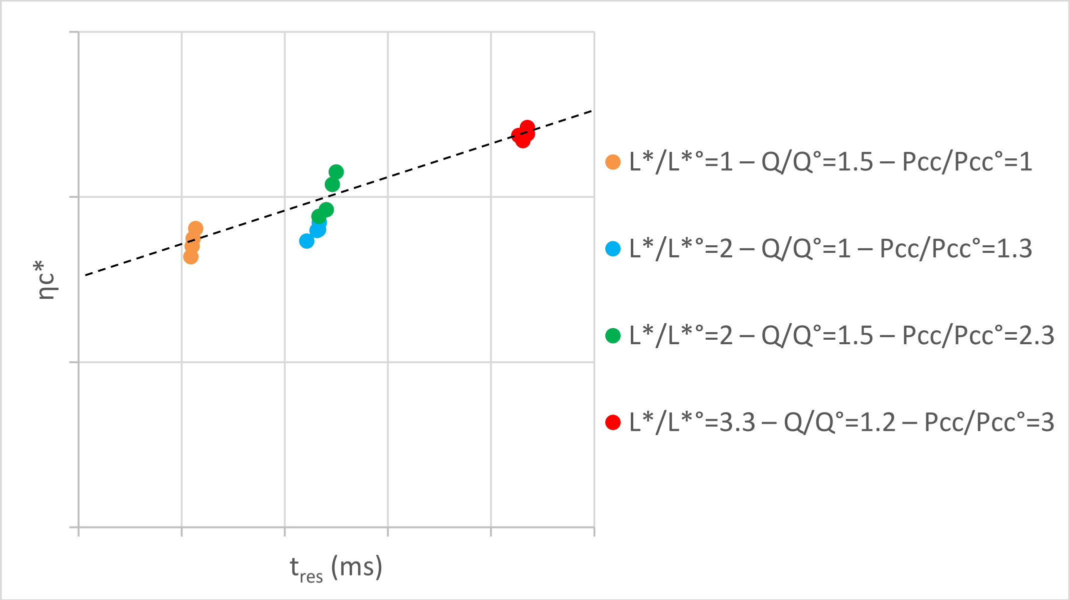

Figure 12: Evolution of the characteristic velocity efficiency versus residence time

Compared to our previous work at reduced scale [8], both c* and its efficiency are somewhat lower in the present configuration because of the residence time: its order of magnitude is 10 ms in the present study versus 50 ms in [8]. This is the reason why, in the present study, L* and combustion pressure have been increased so as to generate a longer residence time that yields a higher combustion efficiency.

4 Conclusion

A dedicated facility was built at PPRIME Institute with the support of CNES to investigate fundamental aspects of storable bipropellant combustion, in representative conditions (TRL 4, large-scale but not full-scale). PERGOLA features a non-catalytic ignition of non-hypergolic propellants, leading to stabilized operation at elevated pressure and flowrate. This unique experimental setup allows the safe implementation of storable propulsion in a laboratory environment adapted to time-resolved physical diagnostics.

A validation study of PERGOLA facility was carried out using miscible green propellants, namely ethanol and hydrogen peroxide. Injection was performed by conventional like-doublet impinging jets. The operation of this bipropellant system in an opaque combustor exhibited a stable combustion regime with choked flow condition, and provided an evaluation of the combustion pressure, wall heat flux and propulsive thrust. The analysis of combustion efficiency, through characteristic velocity and its efficiency, pointed out the effect of residence time on the progress of combustion reaction, hence on combustion efficiency. This confirmed the need to work at elevated pressure or characteristic length, ultimately to reach the highest specific impulse.

As a result, PERGOLA proves to be a validated research facility, that will allow PPRIME and CNES to investigate the combustion stability and propulsion performance of some prospective couples of storable propellants. Advanced green propellants are expected to be characterized in future work.

Acknowledgments

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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] K. Sakaki, S. Nakaya, M. Tsue and T. Hiraiwa, 2009. Fundamental combustion characteristics of ethanol/LOX rocket engine combustor with planar pintle type injector. *Trans. Japan Soc. Aero. Space Sci*. 58: 15–22.