L. Vingert, G. Ordonneau, N. Fdida, P. Grenard
(ONERA)

E-mail: lucien.vingert@onera.fr

DOI : 10.12762/2016.AL11-15

A Rocket Engine under a Magnifying Glass

Even though the technology of cryogenic rocket engines is well mastered today, and has been applied successfully in many launchers all over the world, research activities on the various elementary or coupled processes involved in these complex systems are still relevant and useful for future developments, cost reduction, and knowledge improvement.
The Mascotte test facility was designed and built with this in mind twenty years ago. Since then, numerous configurations have been tested, enabling almost all of the phenomena involved in the operation of a rocket engine to be investigated, in a research lab environment, but nevertheless under representative conditions.

Research items addressed on the Mascotte test rig include: injector concepts; liquid oxygen jet atomization and combustion, new propellant combinations (methane instead of hydrogen), ignition, heat transfer at the chamber walls, high frequency instabilities, flow-separation in an over-expanded nozzle, plume and infrared signature.

Introduction

Chemical propulsion relies on the principle that energy is stored in the chemical reactants and supplied to the system through exothermic reactions. Despite the fact that reactants have a fixed amount of energy per unit mass, which limits the achievable exhaust velocity or specific impulse, and because the propellants are their own energy source, the rate at which energy can be supplied for propulsion is independent from the propellant mass. Thus, very high powers and thrust levels can be achieved. Among the numerous available propellants, the hydrogen/oxygen combination is the most efficient in terms of specific impulse. Even though the development of a device often precedes detailed understanding of the phenomena prevailing there, for instance liquid oxygen/hydrogen (LOX/H2) was envisaged for J2 and RL10 engines at the end of the fifties and used in the Apollo program, the best use and optimization of an engine performance are possible only if the basic physical phenomena and their coupling are well understood and described. These various items require well instrumented testing, modeling and research activities. It is the reason why many teams all over the world have worked on this subject for decades, and still do.

It is indisputable that the technology of cryogenic rocket engines is well known today, and that it has been applied successfully in many launchers (Saturn V, Ariane 1 to 5, Space Shuttle, H-II, etc.), but the low cost development of such complex systems, which have to be increasingly performing and reliable, is still a big challenge for the manufacturers, even more so with reusability, which appears as the main driver for future applications [1]. In addition, in recent years, the propellant combination liquid oxygen/methane (LOX/CH4) has attracted considerable attention in the USA, Europe and Japan for attitude control, upper stage or booster engines. Methane has two advantages over hydrogen, which compensates for the slight loss in specific impulse: its higher specific mass and the proximity of its thermal characteristic to those of oxygen, especially its liquefaction temperature. Both permit cost reduction through simplification of the stage: smaller tank volume and easier to handle cryogenic technology, thanks to the higher temperature, around 100 K instead of 20.

Up to now, the standard practice in the design of space propulsion systems has mostly relied on accumulated know-how and trial and error methodologies, even though computational tools have been progressively introduced in the design process, taking advantage of the increase in computational power. Nevertheless, numerical codes need to be validated on detailed experimental results, gained under well controlled, but as representative as possible, operating conditions. With this objective in mind, ONERA designed the Mascotte test bench to examine a broad range of processes controlling the combustion of cryogenic propellants, such as atomization, droplet vaporization, combustion at high pressure under subcritical and transcritical conditions, etc. Other topics of major importance in liquid rocket engines, like ignition, combustion instabilities, heat transfer and nozzle flow separation, are investigated too. It was initially decided to work on single injector configurations fed with cryogenic propellants under representative pressure and temperature conditions, but the more recent studies of ignition and high frequency instabilities were carried out on multiple injector configurations comprising up to five units arranged in a row or as a pack. The first years of Mascotte were devoted to the progress, in three directions in parallel. The first one was to increase the operation domain by progressively exploring high pressure conditions and reaching supercritical conditions of the type prevailing in cryogenic engines. The second point was the development of advanced and non-intrusive optical diagnostics adapted to these extreme conditions. These included high resolution spectroscopy, backlighting, OH* emission imaging, Planar Laser Induced Fluorescence (PLIF) of OH radicals, Raman scattering of oxygen and Coherent Anti-Stokes Raman Spectroscopy (CARS) of H2 and H2O molecules. The third work package was the building of an experimental database through intensive testing.

A number of research projects were carried out in the basic configuration of a coaxial injector fed with liquid oxygen and gaseous hydrogen. It was first important to examine the flame structure, stabilization process, operating parameter effects, pressure effects, processes controlling transcritical combustion and geometrical effects associated with the recess of the liquid oxygen channel. At the start of this experimental program, it was not known whether the flame was stabilized aerodynamically at a distance from the injection unit or whether the flame was attached to the injector unit or close to that unit. There were no data, at least in the open literature, that provided this information. While most experts believed that the flame was formed at a distance from the injector unit because of the very large velocities characterizing the hydrogen stream, the data gathered in the first experiments at low pressure (1, 5 and 10 bar) clearly indicated that the anchor point was very close to the oxygen channel lip. This contradicted initial beliefs and gave a lot of insight for engineering design. This essential finding was supported by direct emission imaging of the flame and by combined imaging using, for the first time in the case of cryogenic flames, Planar Laser Induced Fluorescence of OH and tomographic imaging of laser light scattering. Another important milestone was the application of Abel transform methods to emission imaging data. This tomographic technique allowed a slice of the mean flame to be extracted from imaging data gathered by line of sight techniques. It was the first demonstration of this method and its application to cryogenic flames. Again, these flame structures clearly indicated that emission from OH* radicals began in the near vicinity of the injector unit. The Abel transform method has since been applied in most studies where the mean flame structure is axisymmetric. Another issue of considerable engineering consequence was to understand the effect of a recess of the LOX channel. The recess that is typically adopted in rocket injectors is of the order of one diameter. Emission imaging combined with Abel transform techniques provided the fundamental information required to characterize the change of flame expansion rate due to the recess. Many of the studies performed at that time within the framework of the Coordinated Research Network "Combustion in liquid rocket engines" were summarized in previous review papers [4], [15], [42]. The effects of operating parameters were also extensively documented. It was in particular shown that the momentum flux ratio determined to a large extent the flame structure by directly influencing the quality of atomization. The momentum flux ratio was used in most studies dealing with the atomization and combustion processes at subcritical pressures, as in [8], [10], [11], [23] and [30]. The effect of pressure and in particular the structure of cryogenic flames under transcritical conditions was investigated during the later years of the 1990th and reported in [17]. This article describes the structure of cryogenic flames formed by injection of liquid oxygen and gaseous hydrogen at pressures exceeding the oxygen critical pressure of 5.04 MPa. The data was supplemented a few years later with images obtained from PLIF of OH at a pressure of 6.3 MPa. This dataset is perhaps the only one today that corresponds to laser induced fluorescence imaging at very high pressure [39].

The extension of the Mascotte test bench, which took place in a second stage [43] allowed new studies of flames formed by liquid oxygen and methane [46]. This has led to some unique findings [37], with in particular the first detailed analysis of flames formed by liquid oxygen and gaseous or liquid methane. The peculiar structure of liquid oxygen/liquid methane flames will be described later in this article. Much of the effort carried out up to the year 2005 was summarized in [5] and in [14]. Further work on liquid oxygen /methane flames was carried out with laser induced fluorescence imaging and emission imaging techniques. These allowed a detailed analysis of the flame structure up to a pressure of 2 MPa [38], [40]. In parallel, the CARS technique was adapted to use the methane as probe molecule [2] and later, a unique coupling between two CARS systems sampling simultaneously H2 and H2O [13] was operated within the framework of the European "In Space Propulsion" program[28]. The problem of flame stabilization was also revisited, by comparing the near field structures of liquid oxygen/gaseous hydrogen and liquid oxygen/methane flames [41]. This was used to verify a stability criterion derived in [18]. On a more practical level, a number of injector design issues have been considered. This is the subject of references [6] and [9] and will be used later on as an example of application of the test bench.

Much of the recent work on the Mascotte facility was carried out within the framework of the French-German REST (Rocket Engine Stability) program dealing with high frequency instabilities in rocket engines. Studies have been focused on the interaction between transverse acoustic waves and multiple flames established in a rectangular chamber equipped with large visualization windows and comprising an external actuator. A remarkable coupling observed in this configuration was reported in References [31] and [32]. Further experimental data were obtained using a novel actuator concept: the Very High Amplitude Modulator (VHAM). This was specifically intended to obtain very high amplitude levels of modulation in the transverse direction. It was thus possible to obtain acoustic pressure fluctuations in excess of 20% of the mean chamber pressure and to observe the interaction between multiple flames and transverse acoustic oscillations induced by the VHAM. An initial demonstration of the VHAM is proposed in [21]. Some experimental results obtained with the VHAM are reported in [22]. The VHAM was also used successfully in the very high pressure range (above the critical pressure of oxygen) and results obtained were used to validate a full Large Eddy Simulation of the Multiple Injector Combustor mounted on the Mascotte test bench [16]. Much of the data gathered on the Mascotte test bench has served to validate the new Large Eddy Simulation derived in recent years to calculate transcritical flows with combustion. This is exemplified in [36] where the case of a liquid oxygen /gaseous methane flame is considered. It is shown that the calculation retrieves most of the flame structure features and provides a good prediction of the flame length.

Another topic of considerable practical consequence is that of heat transfer to the chamber walls. This has been considered in a series of studies [7], [27], [29], [45] and some results will be used to illustrate this point. An aspect that also deserves attention is that of ignition.

Of course, it is difficult to represent conditions prevailing in the real engine at the start, but it is nevertheless interesting to examine ignition and subsequent flame spreading in a well-controlled set-up. The data could then be used for code validation. This is illustrated in [24], [35] and [44] and used as an example later in this article. The Mascotte facility has also been used to look at problems that do not concern the thrust chamber, but are closely related, such as the plume and infrared signature [3], [33], or the dynamics of the flow in the divergent part of the nozzle. Detailed measurements using state of the art laser diagnostics have been used to examine the possible combustion of the rich gases exhausted by the chamber with air entrained from the ambient atmosphere in the region of flow-separation in an over-expanded nozzle [25], [26] and [34]. This will be described in further detail in a later section of this article.

The previous review gives a synthetic view of the broad collection of results obtained using the Mascotte facility and underlines some of the highlights of research carried out with this test bench. Much more is available in the original references and no attempt will be made to bring these together. In what follows, after a brief presentation of the Mascotte test rig, we examine a set of four illustrative cases. § "Ignition" is concerned with ignition. Atomization is discussed in § "Atomization". The problem of flow separation in the nozzle is briefly considered in § "Flow separation in an over-expanded nozzle". Studies on heat transfer to the chamber walls are briefly described in § "Heat transfer" and a few other topics are mentioned in § "Other topics.

The Mascotte test facility

A brief history

The Mascotte test rig was developed at the beginning of the 90s to experimentally investigate the basic phenomena that occur in the combustion chamber of a cryogenic rocket engine, especially in the vicinity of a coaxial injector fed with liquid oxygen (LOX) and gaseous hydrogen (GH2). The research conducted there is linked to the need to continuously increase the performance and the reliability of the launchers, while simultaneously reducing costs and development times [15]. The objectives are to improve the knowledge of cryogenic propellants combustion, including dynamic aspects, to create an extended experimental data base, which will be later used to validate numerical codes, and to facilitate the selection of innovative technological concepts.

Successive versions were developed over the years to increase the operating domain and to extend the possibilities to new subjects. Versions 1 to 3, operated from 1994 to 2001, were dedicated to the LOX/H2 combustion studies, from atmospheric pressure, up to 70 bar [42]. The latter lies in the supercritical domain of oxygen, were most of the actual rocket engines operate (the critical pressure of oxygen is 50.4 bar) [5]. Various combustion chambers may be used, all equipped with optical access, like the one shown in Figure 1, which is a single-element combustor. In 2002, the facility was improved to offer the possibility to burn methane, in gaseous or liquid state, as well as hydrogen. This extension is referred to as version 4 [43]. During the period 2002-2005, new research topics were addressed, including dynamic aspects of the combustion like ignition, flame propagation with multi-element injection plates and instabilities at low and high frequency. Flow separation in over-expanded nozzles and also more technological considerations, for instance new injector's concepts, were investigated too. The present version 5, in operation since 2006, allows the use of gaseous oxygen at room temperature, while only liquid oxygen was available before. But the main change between versions 4 and 5 is related to the combustion chamber rather than to the test stand itself: a water-cooled chamber was designed and built that can be operated at a mixture ratio as high as 7.5 (oxygen/hydrogen), which is representative of thrust-chamber conditions, while the previous combustors, all based on the heat-sink technology, were limited to a mixture ratio of 3, and were therefore more suited for gas-generator studies. With this increase to more severe experimental conditions, a significant effort was also put on the improvement of safety and quality.

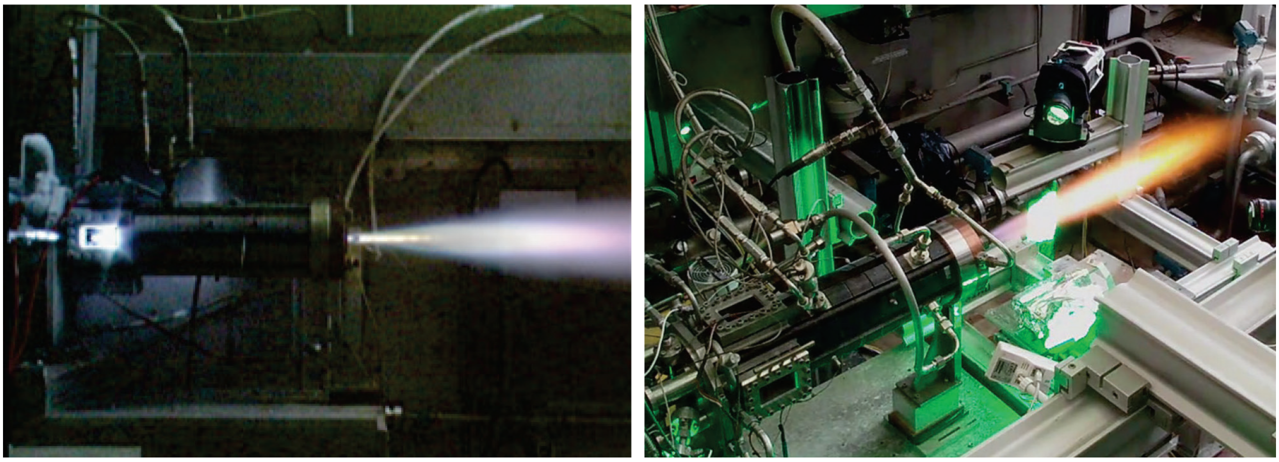


Figure 1 - Mascotte LOX/methane hot fire tests. Both cases: chamber pressure ≈ 10 bar, mixture ration ≈ 1.5
Left: liquid/gas injection Right: gas/gas injection with PIV in the plume.

Main characteristics - operating domain

With its main characteristics, recalled in Figure 2, Mascotte lies in an intermediate range, between laboratory scale setups and full scale industrial test rigs, with a dual purpose of investigating cryogenic propellants combustion and at the same time develop and apply advanced diagnostics [14] like Coherent Anti-Stokes Raman Spectroscopy [2], [13], Planar Laser Induced Fluorescence [25], [40], Phase Doppler Particle Sizing [11], Particle Image Velocimetry [9], [26]... Complementarity with the DLR means, P8 and M3, of the Space Propulsion Institute in Lampoldshausen may also be mentioned [15].

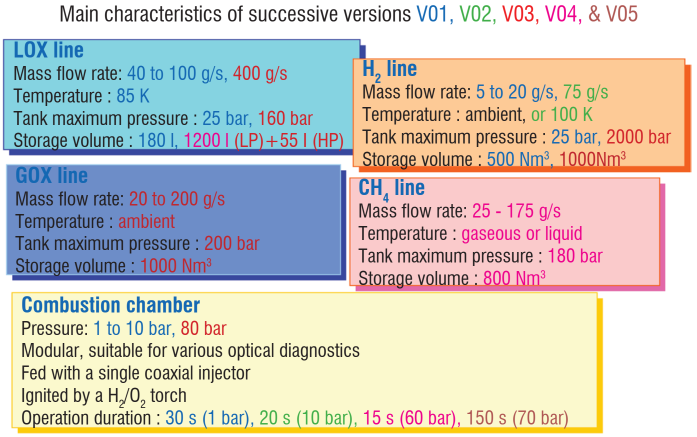


Figure 2 – Main characteristics of Mascotte

Ignition

Ignition of cryogenic rocket engines is still a challenging issue. It became critical in Europe in the mid-eighties when hard starts were responsible for flight failures. At that time, manufacturers and space agencies had to deal with the emergency of flight recovery, and the problem was fixed by purely empirical means. Today, the specifications of the European engine VINCI, which is an expander cycle engine, include the ability of successive re-ignitions during the flight. The problem is therefore again of major importance, a framework in which CNES and ONERA, together with DLR, decided to follow a more scientific approach to the topic [24]. With this objective, specific test series were run on Mascotte [44] and on the DLR Lampoldshausen M3 facility [35]. The main difference lies in the ignition procedure: an H2/O2 torch as in an actual engine on Mascotte, and laser ignition on M3. The latter certainly yields more detailed information on the basic physics of the primary ignition phase and on the flame front velocity, but it has to be completed with more representative conditions, which is in fact the objective of on-going activities at the DLR P8 facility. Using laser ignition is indeed an option for future launcher evolutions. The main objective of the Mascotte test series was to characterize the influence of fuel injection on the ignition process. The parameters that were varied are the nature of the fuel (hydrogen or methane) and its injection velocity (i.e., mass flow rate), while all other parameters: geometry, test sequence and liquid oxygen flow, were maintained constant. A combustor equipped with large windows (Figure 4), fed by three coaxial injectors and ignited by a hydrogen/oxygen torch placed on the top of the chamber, was used for this purpose. Figure 3 shows the successive ignitions of the three injectors recorded at 25 frames per second.

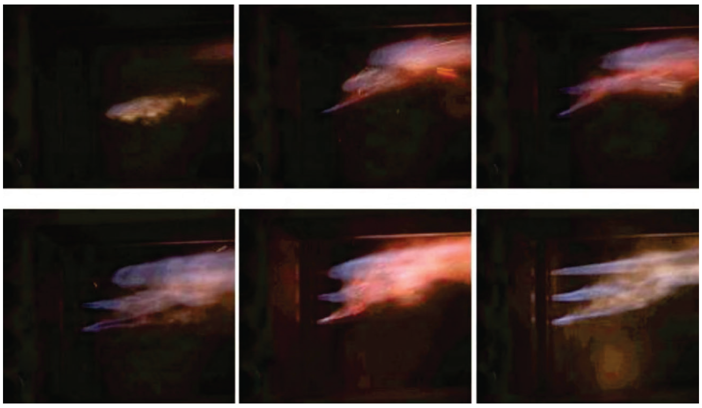


Figure 3 – Successive ignitions of the three jets(40 ms between 2 images)

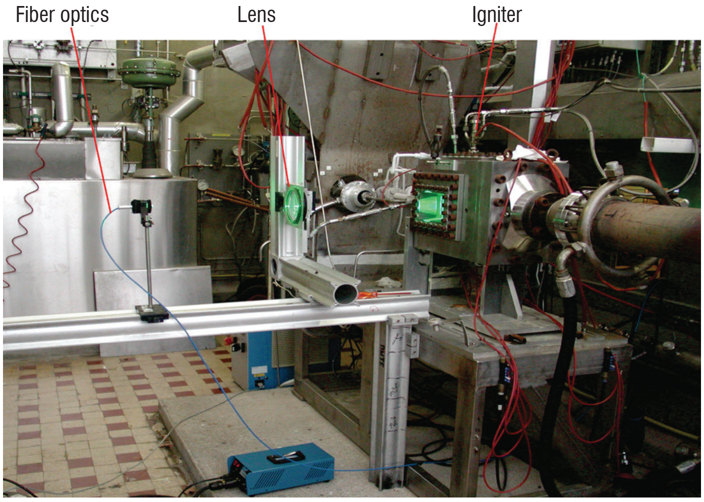


Figure 4 – Experimental setup: shadowgraphy with a laserstrobe as light source

The ignition process was recorded by means of two high speed digital video cameras. The first one (Phantom V4), operated by ONERA, was devoted to the visualization of the phenomena in the visible light range and the second one (Photron APX), operated by DLR, recorded the flame emission in the ultraviolet spectral band (i.e., the emission of the OH* radical at a wavelength of 306 - 320 nm). Both cameras were synchronized to the test stand monitoring and measurement acquisition systems. Besides the main parameters of the feed lines upstream of the injectors, three dynamic pressure transducers were recorded at a data rate of 40 kHz. The injection valve opening and torch ignition signals were also recorded at the same acquisition rate, in order to ensure that all devices were reproducible enough to state that any variation observed in the ignition delay was actually due to the physics, i.e., to a change in one of the investigated injector flow parameters, and not to any dispersion in the test sequence. Experiments corresponding to the various operating conditions were repeated four times: once with hydrogen and once with methane, and for two locations of the igniter. The operating points with the two fuels are very similar, in terms of dimensionless numbers (momentum flux ratio J and Weber number We). Figure 5 shows the reproducibility of the automatic sequence for the 58 acceptable tests. It appears that only the LOX valve response time is a little dispersed, but this has no incidence on the rest of the process, because we used a LOX-lead sequence. The opening of the LOX valve is the first event and, due to its size, its internal cross section becomes bigger than that of the cavitating venturi, which is used to regulate the LOX flow as soon as it is open a few per cent. This is confirmed by the LOX injection pressures recorded for the same 58 tests (Figure 6): only run 56 is completely out of the family.

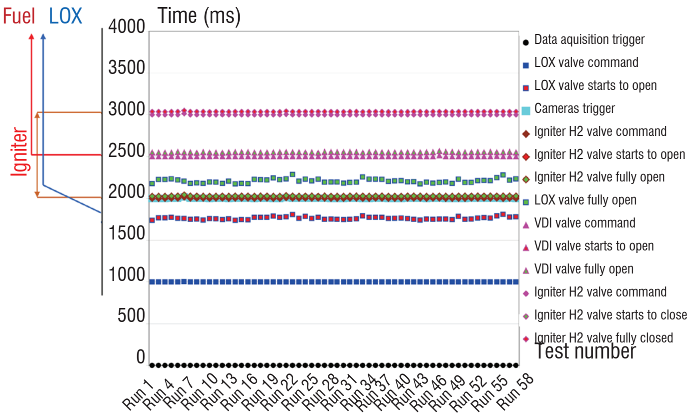


Figure 5 – Test sequence reproducibility
(valves response and opening times in ms)

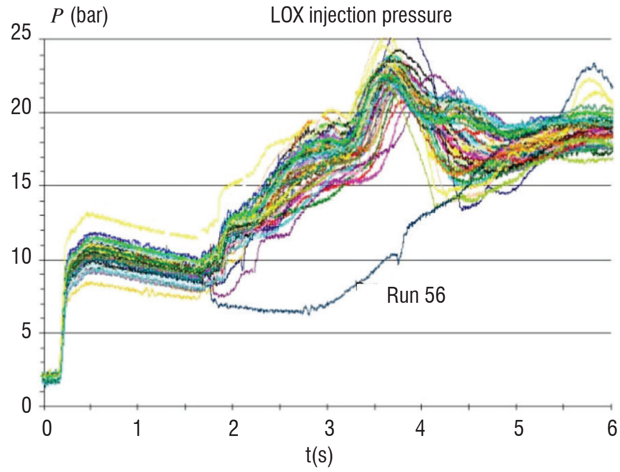


Figure 6 – LOX flow reproducibility (LOX injection pressure)

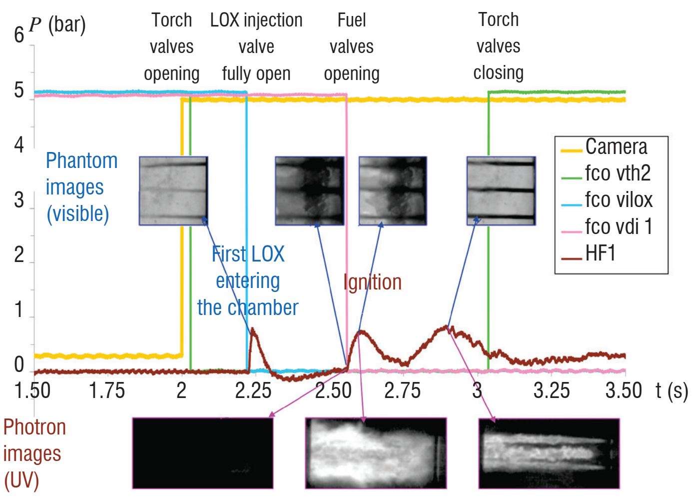


Figure 7 – Typical test: automatic sequence, dynamic pressure and images

The chamber dynamic pressure measured by means of a Kistler transducer located at the bottom of the combustor, in front of the igniter upstream position, has a similar time evolution for all validated tests (shown in Figure 7), with a first peak due to the chemical reaction between the first oxygen entering the chamber and the hot gases produced by the fuel rich igniter. The actual ignition of the jets, however, occurs only at the opening of the fuel valve and this corresponds to the second peak. This is confirmed by the images of the Photron camera (bottom images): no OH* radical emission is detected near the injectors before the second pressure peak. The third maximum is not well identified by the images: it happens during the stabilization phase of the flames on the lips of the LOX posts.

Figure 8 shows that the time delay between the opening of the fuel valve and the occurrence of the pressure overshoot decreased with the fuel mass flow rate (the fuel upstream pressure). A correlation equation can be found, with a correlation coefficient R^2=88% for the hydrogen tests. The methane tests are a little more scattered (R^2=60%), but the trend is clearly the same. It appears also that the ignition of the jets is delayed by around 50 ms when methane is used instead of hydrogen.

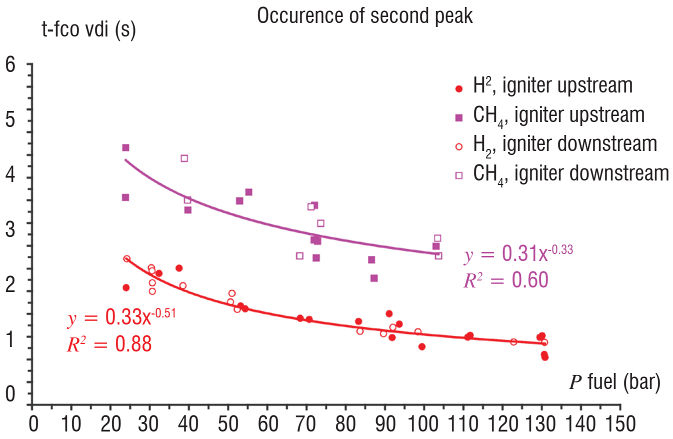


Figure 8 – Time delay between the fuel valve opening and pressure peak at ignition

Atomization

Injectors of cryogenic liquid rocket engines produce large polydisperse and dense sprays (Figure 9) due to the pressure and mass flow conditions. Atomization is the dominating process that drives the flame behavior in cryogenic jet flames, when the propellants are injected in subcritical conditions. The characterization of a liquid oxygen spray in gaseous hydrogen, under reacting conditions, was carried out on the Mascotte test bench [10] to complete the existing database [11] on a reference operating point, used as a test case for numerical simulation [23], [30]. In the breakup region, where liquid fragments detach from the LOX jet to disintegrate into smaller elements, liquid particles are not spherical. Since laser based drop size techniques make the assumption of spherical particles, they suffer from a low validation rate and thus imaging techniques can be better suited to characterize the spray. High speed shadowgraphs were used to provide the spray characteristics, such as sizes and velocities of the LOX dispersed phase atomized by a GH2 co-flow injected by a shear coaxial injector in a 10 bar combustion chamber.

The reacting case was compared qualitatively to a cold flow test, with helium instead of hydrogen, for which LOX spray shadowgraphs were also recorded. The morphology of the LOX jet at the injector exit was illustrated with small sized images, recorded at high frequency, for cold and reacting conditions, similar in terms of Reynolds and Weber numbers. The cold LOX jet was constituted by an envelope of small droplets

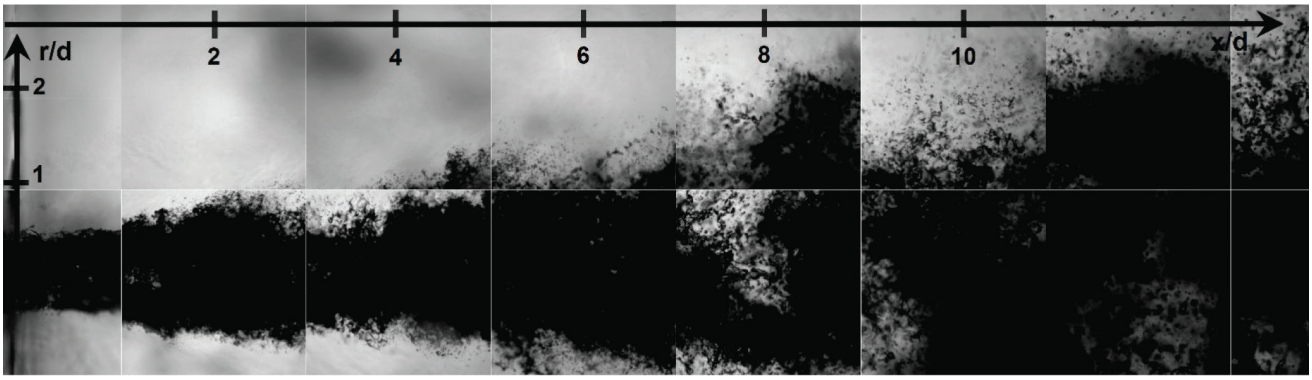


Figure 9 – Liquid oxygen jet structure at 10 bar (1 MPa)

around the LOX core, whereas in the reacting case, those small droplets were not present and larger liquid structures were revealed. The flame filters the smallest structures by vaporizing them from the beginning of the jet at the LOX post exit. The droplet sizes of the spray were obtained in the first and secondary atomization zone. The Sauter mean diameter evolution with axial distance showed a slight decrease towards the smallest diameters from $x/d=$ 6 to 12, at a radial distance of $r/d=2$, where d is the LOX post diameter. Far from the injector ($x/d=18$), the Sauter mean diameter was found to be similar to that measured in Ref. [11], with a Phase Doppler Particle Analyzer (PDPA). However, close to the injector, at $x/d=6$, where droplets are not spherical, size measurements were not in agreement and difficult to compare because the PDPA validation rate was very low in this area. The probability density functions pdf, illustrated in Figure 10, showed some features of such a burning spray: a large shape that seemed to be translated towards larger diameters, as the axial distance from the injector increased, which is probably due to droplet vaporization.

The velocity of the dispersed phase under reacting conditions was obtained with two different imaging methods, which were applied to the same shadowgraphs: a PTV (Particle Tracking Velocimetry) algorithm and PIV (Particle Image Velocimetry) software, FOLKI-SPIV, developed at ONERA. Velocity measurements obtained with both algorithms showed that droplet velocities decreased by a factor of 3 from $x/d=6$ to $x/d=12$. The droplet size was combined with PTV to obtain the droplet size/velocity correlations, presented in Figure 11, which are essential to understand the dynamics of the dispersed phase. The smallest droplets were decelerated more rapidly than the larger ones because, having less inertia, they are more sensitive to the aerodynamic forces in the turbulent flame. Close to the injector exit, at $x/d=6$, all droplets, whatever their size, were ejected with the same velocity. This particular area of the spray could indicate the first atomization zone where the droplet velocity comes from the liquid jet.

The velocity of the dispersed phase was also obtained with FOLKI-SPIV applied directly to shadow images. This method can be useful to obtain information on such a LOX spray, which is not compatible with most seeding particles. PIV and PTV algorithms agreed well in terms of U, V mean velocity and radial profiles in the investigated areas. FOLKI-SPIV gave better results in terms of the cross-correlation score and agreement when using a large interrogation window 99 pixels wide. In areas where the droplet density was not high enough, both methods diverged and we could not conclude in areas where the gas phase is in majority. Thus we chose to mask those areas where the algorithm was less reliable than PTV in terms of score.

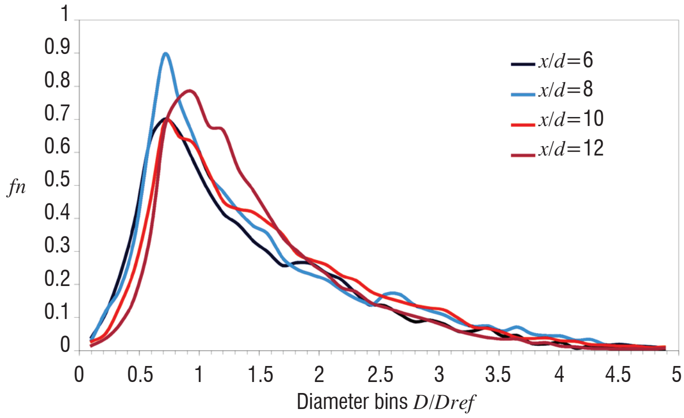


Figure 10 – Drop size distribution (pdf) evolution towards the injection axis from $x/d=$ 6 to 12, at a radial distance of $r/d=2$.

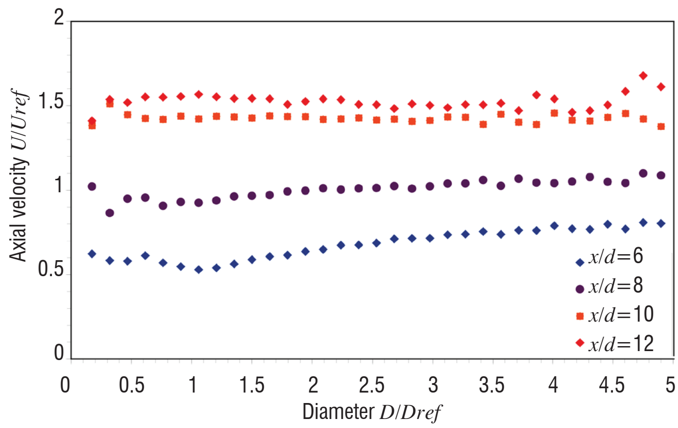


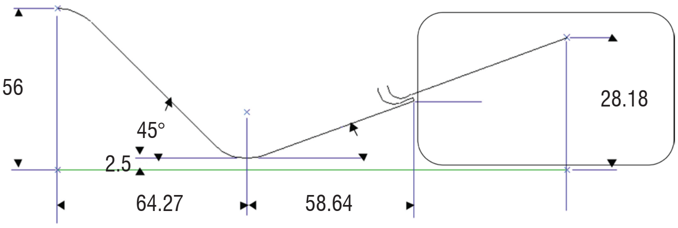
Figure 11 – Mean droplet axial velocity measured by PTV as a function of diameter class, evolution towards the injection axis from $x/d=$ 6 to 12, at a radial distance of $r/d=2$ (reacting case).

Flow separation in an over-expanded nozzle

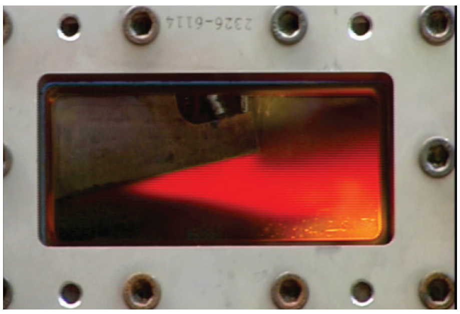
The thrust delivered by a rocket engine depends on the combustion pressure, but also on the performance of the nozzle, which is characterized by its aspect ratio ε equal to the exit area divided by the throat area. The thrust increases with respect to the aspect ratio, while the pressure at the nozzle exit decreases in the same proportion. Knowing that the nozzles of the first stage of a launcher have to operate in a large range of ambient pressures, from sea-level atmospheric conditions (10^5 Pa) to very low pressure conditions at high altitude (10^{-5} Pa), it appears that, at the very beginning of the flight, the wall pressure level required for an adapted attached flow can be much lower than the ambient pressure. This leads to a flow separation in the nozzle extension. In addition, due to the high level of stagnation enthalpy in liquid-rocket nozzles, the wall of the nozzle extension is exposed to high heat fluxes. These can be overcome by using a cooling film. The problem is that the film has to remain efficient all along the wall, even if an over-expansion shock interacts with it.

Within the joint CNES-ONERA research program on nozzle and after-body aerodynamics (ATAC), a general test plan for the establishment of a database for the validation of aerothermochemical codes has been drawn. The experimental set-up consists of a 2D nozzle operating with hot gases resulting from oxygen/hydrogen combustion. The first test series, aimed at investigating the re-ignition process and obtaining a correlation between pressures and temperatures at the walls, which are the only measurements available on a full-scale nozzle [25]. In addition, optical measurements, such as Planar Laser-Induced Fluorescence (PLIF), Particle Image Velocimetry (PIV) and Coherent Anti-Stokes Raman Scattering (CARS), previously successfully applied in a study on reactive rocket engine plume [33], are required to characterize the aerothermomechanical flowfield in the separation zone for various separation configurations (i.e., without separation, incipient separation and effective separation) corresponding to stagnation pressures from 20 to 60 bar.

For this purpose, it was necessary to design a planar geometry for the sub-scale nozzle, in order to fit it with appropriate windows, and to meet several criteria linked to the operating conditions of the set-up and to the aerodynamic pattern of the flow field. These were chosen to ensure similarities with nozzles planned for future launch vehicles. Moreover, the geometry had to be optimized, in order to obtain a sufficiently large recirculation zone where optical measurements can be performed. The main geometrical characteristics of the nozzle profiles are presented in Figure 12a. The nozzle width is 26 mm. One of the most critical parts of the nozzle is the 1 mm lip, where the film is injected, which is subject to high thermal stress.



a) Geometrical characteristics of the nozzle with window



b) flame in the separated zone

Figure 12 – The two-dimensional nozzle of the ATAC program

Currently, PLIF on the OH* radical [26] was used to analyze the combustion region in the nozzle (Figure 13). The laser pulse was emitted by a Nd:YAG pumped dye laser (Quantel YG780 and TDL70) and a doubling crystal. The pumping laser wavelength was tuned to the appropriate transition Q1(3). Among the operating points tested during the adaptation campaign, only those at 25 bar (effective separation) and 40 bar (incipient separation) were retained to perform PLIF measurements.

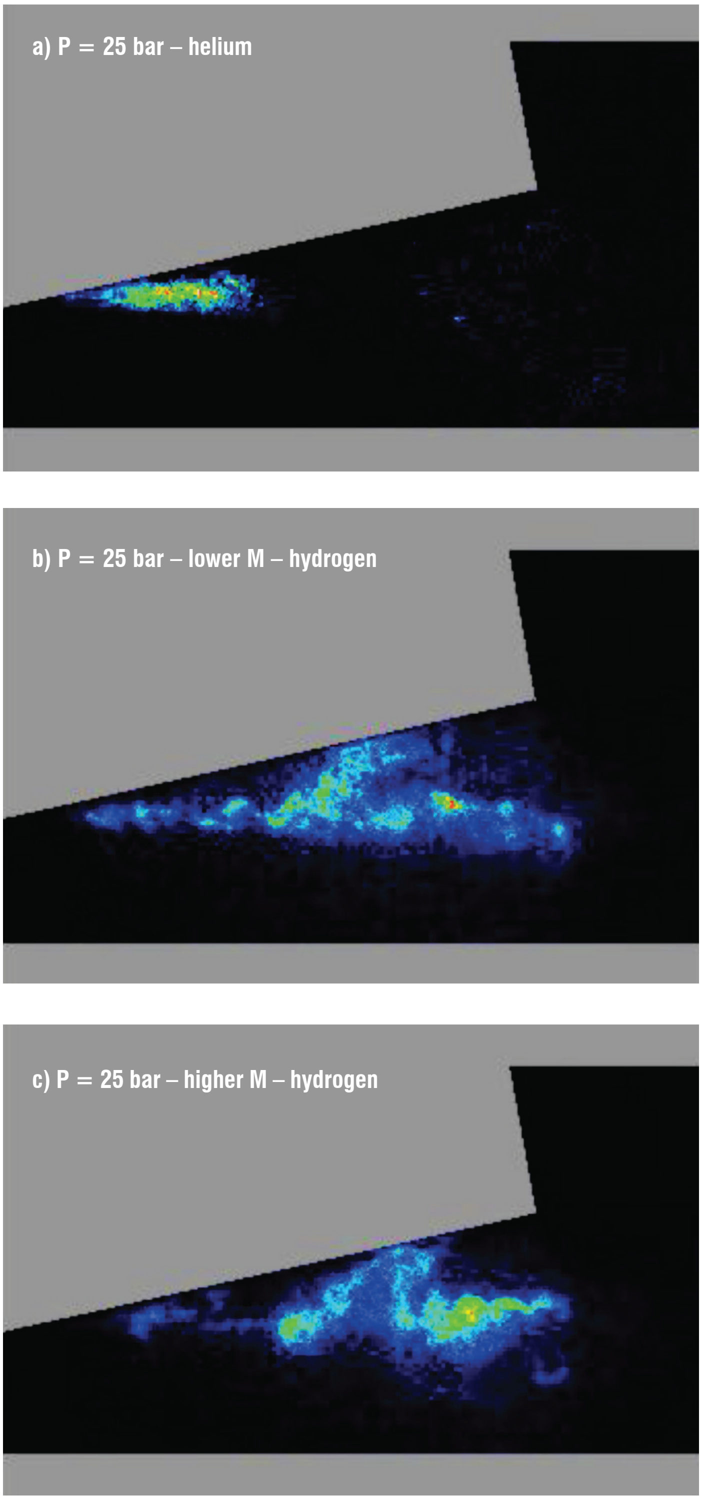


Figure 13 – Instantaneous PLIF images of OH radical concentration

For a 25 bar chamber pressure condition, instantaneous PLIF-OH images show a reactive zone near the upper wall of the nozzle, which indicates that the hydrogen rich jet can burn with fresh air (Figure 13b).

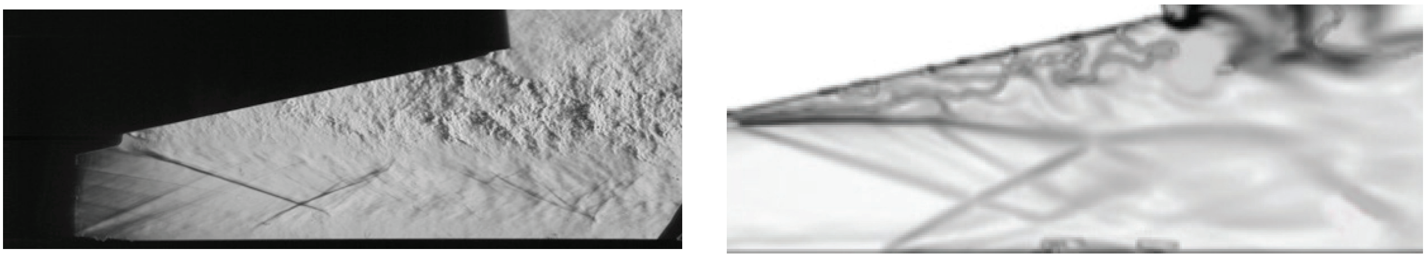


Figure 14 – Flow structures (Experimental (left) – Numerical (right))

If the cooling film is fed with helium instead of hydrogen, this zone has a limited spatial extent and is close to the wall. The fluorescence intensity distribution is quite homogeneous in the reactive zone, whatever the instantaneous image but it shows large fluctuations due to unsteadiness linked to turbulence in the recirculation zone, as shown by the Delayed Detached Eddy Simulation (DDES) in [34]. Moreover, spontaneous OH* imaging at 8 kHz revealed the dynamics of the flow, consistent with pressure measurements. More recently, PIV coupled with Schlieren imaging has been tested in cold flow conditions. Similar experiments are planned with combustion, to map the velocity flowfield in the hot gas flow.

Heat transfer

Heat transfer at the combustion chamber wall is a key issue, directly linked to the lifetime of the combustion chamber for a reusable liquid rocket engine and to the overall performance of an expander cycle motor. It is therefore a challenging field, where the precise evaluation and prediction by numerical tools remains difficult and, due to the high temperature (more than 3000 K in the combustion chamber), only few "global" measurements are available.

In order to better understand and measure heat fluxes at the wall, which is mandatory to improve numerical tools and models able to give an accurate description of those phenomena, a high pressure - high mixture ratio subscale combustion chamber was developed within the framework of the ONERA-CNES CONFORTH project (Figure 15). It is water-cooled, fed with five coaxial injectors arranged in a cross pattern and able to reproduce representative liquid rocket engine conditions (70 bar, O/F=7). The choice was made to overcome the limitations of "global" measurements, such as calorimeter sections, by implementing hundreds of thermocouples on the injector plate, as well as on both the hot gas and cooling fluid sides of the cylindrical segment walls of the combustion chamber.

A first test series was successfully conducted in 2010 [27], from 20 to 65 bar and a mixture ratio from 2 to 7, demonstrating the test domain possibilities of the combustion chamber. Further test campaigns were performed in the time period 2012-2015 [7], [29] in liquid-gas and gas-gas injection conditions, in both the "thermal" configuration, to measure temperature and heat fluxes at the walls and the "visualization" configuration, in order to see the flame shape and atomization process [8]. The obtained running conditions for the thermal campaigns, in a (Pressure, Mixture Ratio) plane is shown in Figure 16. A similar gas-gas and liquid gas point (black circle) can be used for comparison between these two types of flows.

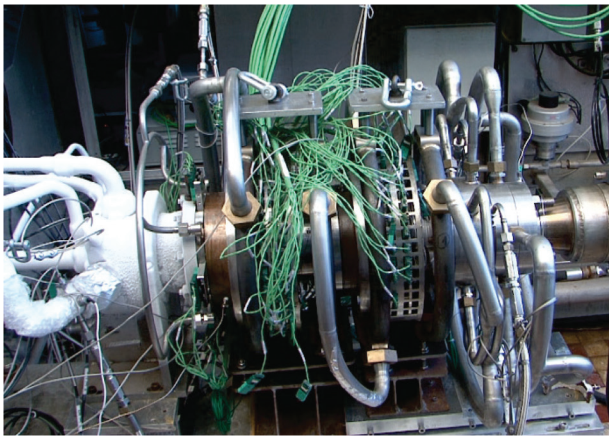


Figure 15 – The High Pressure High Mixture Ratio Combustor of the CONFORTH project

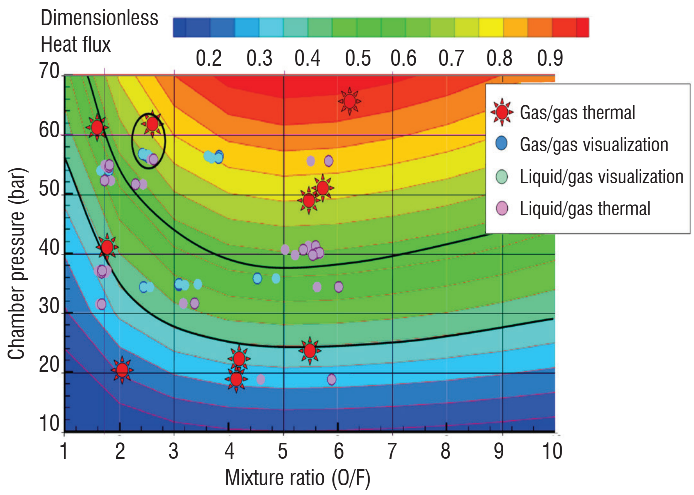


Figure 16 – Heat transfer measurement points obtained experimentally

An example of thermal acquisition of the "hot gas side", versus time, is shown in Figure 17 for this condition. It shows that the overall temperature levels are very similar in both cases, but with greater discrepancy for the liquid-gas condition. Also, the temperature is locally higher in the first segment for liquid-gas conditions, whereas it is higher in the second segment for gas-gas conditions, which tends to indicate that the flame is probably shorter for the liquid-gas condition.

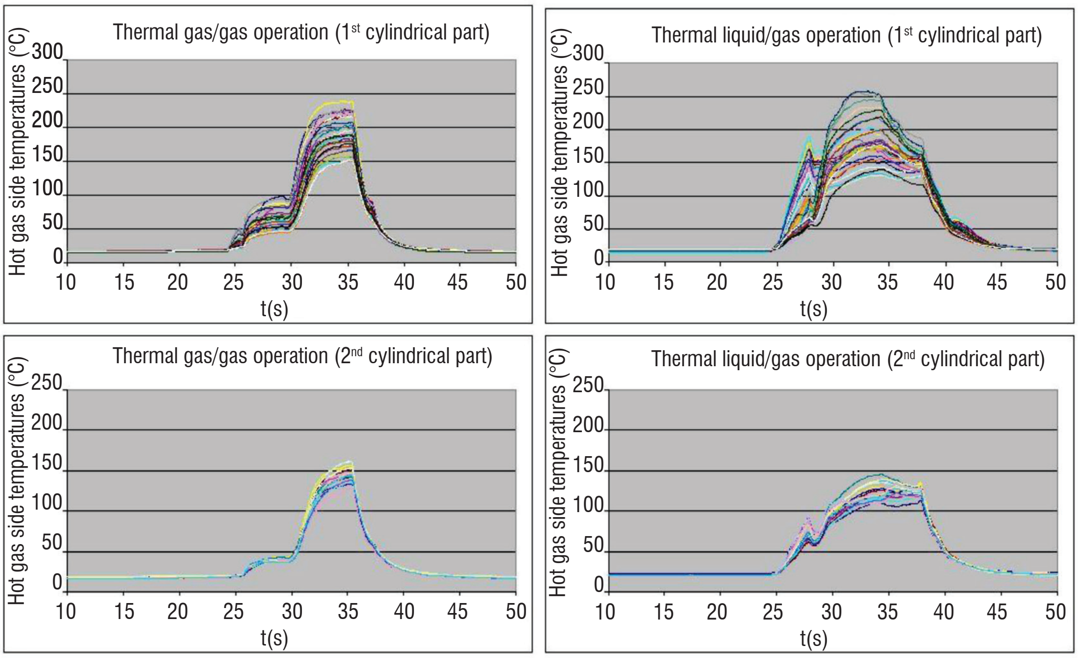


Figure 17 – Experimental measurements for a similar (P,M) condition. Liquid-gas and gas-gas comparison

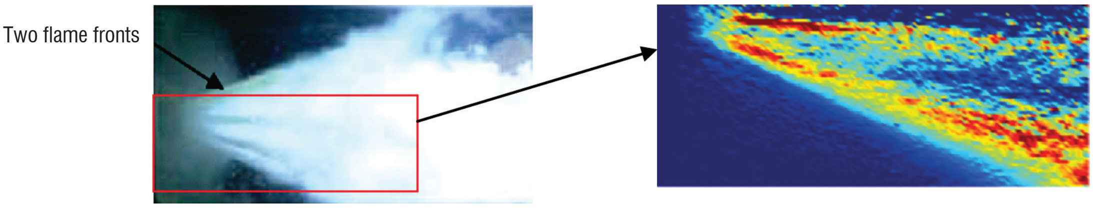


Figure 18 – LOX/LCH4 operation. Left: high speed visualization. Right: OH* chemiluminescence

Other topics

Most of the experiments performed on Mascotte with methane as a fuel were linked to other topics, ignition, high frequency instabilities, etc., mainly to compare how the system, injector or combustion chamber, behaves when it is fed with methane rather than hydrogen. Nevertheless, one point may be mentioned: the heat exchanger installed on the Mascotte fuel line, to cool the hydrogen from ambient to 100 K, is powerful enough to liquefy the methane, enabling liquid/liquid operation. This enabled, for example, the observation of two flame fronts appearing in a coaxial injector flame [37], [40]. This unexpected pattern was emphasized by OH* radical imaging, as well as by high speed visualization in the visible range (Figure 18).

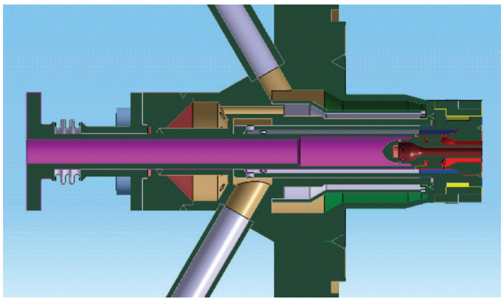


Figure 19 – Sketch of a double-swirl injector

Besides this completely unusual pattern, it has also been stated that the shear coaxial element leads to rather poor performance when operated in liquid/liquid, which is one of the reasons why various injectors concepts like double-swirl (Figure 19 and Figure 21) [9] or confined elements (Figure 20 and Figure 22) [1] were tested.

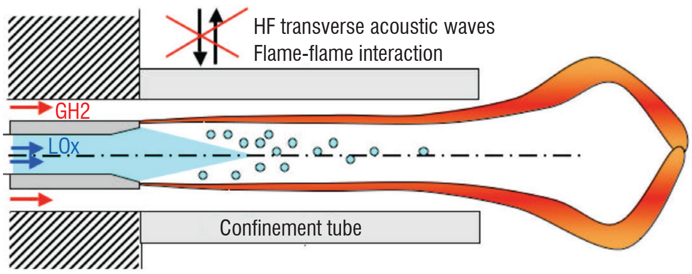


Figure 20 – Illustration of the confined coaxial injector concept

Figure 21 – Hollow cone spray produced by a swirl injector (without combustion, LOX side alone)

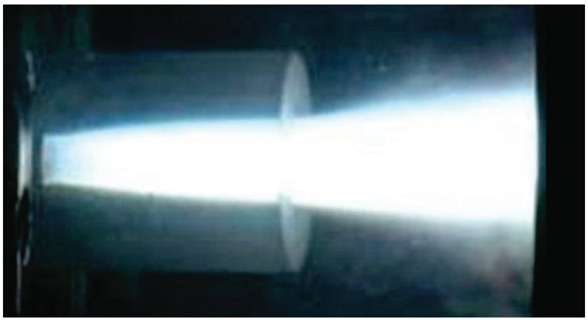


Figure 22 – Operation of a confined coaxial injector

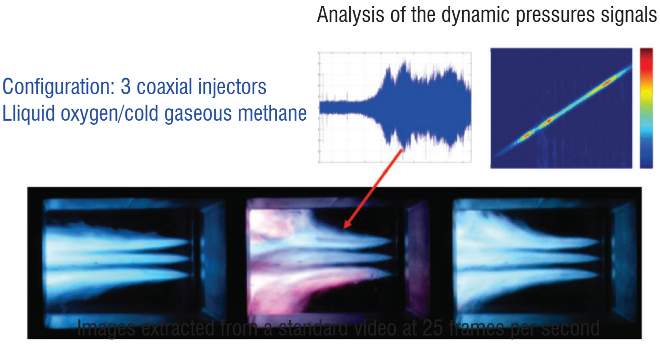


Figure 23 – HF burst observed in LOX/CH4 operation
(flow from right to left on the images of the video)

Several Mascotte test campaigns were dedicated to the study of high-frequency combustion instabilities (HF), firstly with LOX/hydrogen and more recently with LOX/methane [20], [22], [31]. Figure 23 shows an example of HF burst observed in the combustion chamber of Figure 24. In this case, the three coaxial injectors were fed with liquid oxygen and cold gaseous methane. The chamber acoustic modes were excited by means of a toothed wheel, which was accelerated in order to cross all of the modes between 1 and 3 kHz.

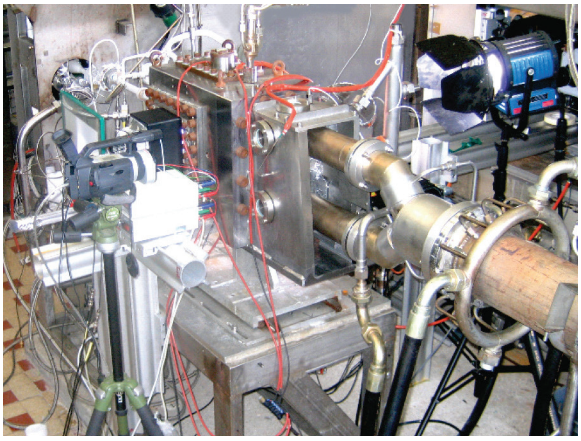


Figure 24 – Experimental setup for HF studies with forced oscillations (Very High Amplitude Modulator)

Conclusion

Twenty years ago, the Mascotte test bench was designed and built to operate under various conditions, from atmospheric to supercritical conditions, with the aim of building a database of combustion around a coaxial jet. During the last decade, numerous new configurations were tested, enabling almost all of the phenomena involved in the operation of a rocket engine to be studied in a lab research environment, but under the conditions encountered in an actual rocket engine. Mascotte remains an essential tool in the understanding of physical phenomena and the development of measuring methods. Moreover, thanks to its flexibility, it allows the testing of new hardware before implementation on larger bench combustors or even actual engines ■

References

[1] L. BOCCALETTO - *A comparison Between Two Possible Thermodynamic Schemes for Reusable LOX/LCH$_4$ Engines*. AIAA Paper 2004- 3356, 2004

[2] E. BERTSEVA, F. GRISCH, M. HABIBALLAH, H. BERGER, F. CHAUSSARD, T. GABARD, E. JOURDANNEAU, R. SAINT-LOUP - *CARS Spectroscopy of CH$_4$ for Temperature Measurements in a Cryogenic Combustion Chamber.* 1st EUCASS, Moscow, Russia, 2005

[3] A. BRESSON, P. BOUCHARDY, F. GRISCH - *Experimental Investigation of a Supersonic Rocket Engine Plume Using OH*-Emission, OH-PLIF and CARS Thermometry*. 11th International symposium on applications of laser techniques to fluid mechanics, paper 16-4, Lisbon 2002

[4] S. CANDEL, G. HERDING, R. SNYDER, P. SCOUFLAIRE, C. ROLON, L. VINGERT, M. HABIBALLAH, F. GRISCH, M. PÉALAT, P. BOUCHARDY, D. STEPOWSKI, A. CESSOU, P. COLIN - *Experimental Investigation of Shear Coaxial Cryogenic Jet-Flame.* Journal of Propulsion and Power. 14, pp. 826-834, 1998

[5] S. CANDEL, M. JUNIPER, G. SINGLA, P. SCOUFLAIRE, C. ROLON - *Structure and Dynamics of Cryogenic Flames at Supercritical Pressure*. Combustion Science and Technology, 178 pp. 161-192, 2006

[6] C. CRUZ, L. VINGERT, M. THÉRON, S. PETITOT, C. VERPLANCKE - *Characterization of Confined Shear Coaxial Injection: LOX/GH$_2$*. 2nd Space Propulsion Conference, San Sebastian, Spain, 2010

[7] L.H. DOREY, P. GRENARD, L. MATUSZEWSKI, L. SELLE - *Experimental and Numerical Study of a Cooled Rocket Combustion Chamber.* 15th International Heat Transfer Conference IHTC15-9238, 2014

[8] N. FDIDA, L. VINGERT, G. ORDONNEAU, S. PETITOT - *Coupling High-Speed Imaging Diagnostics to Study a LOX/GH$_2$ Flame in a High-Pressure Rocket Combustor.* 5th EUCASS, Munich, Germany, 2013

[9] N.FDIDA, L. VINGERT, G. ORDONNEAU, A. RISTORI, C. BROSSARD, R. STÜTZER, J. SENDER - *Characterization of a Double Swirl Injector in a LOX/LCH$_4$ Fueled Combustor on Mascotte Test Bench.* 5th EUCASS, Munich, Germany, 2013

[10] N. FDIDA, L. VINGERT, A. RISTORI, Y. LE SANT - *Droplet Size and Velocity Measurements in a Cryogenic Jet Flame of a Rocket-Type Combustor Using High Speed Imaging*. Atomization and Sprays, under publication, DOI: 10.1615/ AtomizSpr.2015011814, 2016

[11] P. GICQUEL, L. VINGERT - *Flow Investigations of Cryogenic Sprays in Combustion at Sub and Supercritical Conditions*. 16th Annual Conference in Liquid Atomization and Spray Systems, Darmstadt, Germany, 2000

[12] P. GRENARD, L. VINGERT - *CFD Simulation of the GCH4/GO2 Mascotte Test Bench*. 3rd Space Propulsion Conference, Bordeaux, France, 2012

[13] F. GRISCH, L. VINGERT, P. GRENARD, V. FABELINSKY, K. VERSHAGIN - *CARS Measurements at High Pressure in a CH$_4$/O$_2$ Jet Flame*. 4th EUCASS, St Petersburg, Russia, 2011

[14] M. HABIBALLAH, M. ORAIN, F. GRISCH, L. VINGERT, P. GICQUEL - *Experimental Studies of High-Pressure Cryogenic Flames on the Mascotte Test Facility.* Combustion Science and Technology 178, pp. 101-128, 2006

[15] O.J. HAIDN, M. HABIBALLAH - *Research on High Pressure Cryogenic Combustion.* ONERA-DLR Aerospace Symposium, 2000

[16] L. HAKIM, A. RUIZ, T. SCHMITT, M. BOLLEAU, G. STAFFELBACH, S. DUCRUIX, B. CUENOT, S. CANDEL - *Large Eddy Simulations of Multiple Transcritical Coaxial Flames Submitted to High-Frequency Transverse Acoustic Modulations*. Proceedings of the Combustion Institute 35 pp. 1461-1468, 2015

[17] M. JUNIPER, A. TRIPATHI, P. SCOUFLAIRE, J.C. ROLON, S. CANDEL - *Structure of Cryogenic Flames at Elevated Pressures.* Proceedings of the Combustion Institute, 28, pp. 1103-1109, 2000

[18] M. JUNIPER, S. CANDEL - *Edge Diffusion Flame Stabilization Behind a Step Over a Liquid Reactant*. Journal of Propulsion and Power 19 pp. 332-342, 2003

[19] J. LUX, D. SUSLOV, M. BECHLE, M. OSCHWALD, O. HAIDN - *Investigation of Sub- and Supercritical LOX/Methane Injection Using Optical Diagnostics*. 42nd JPC, Sacramento, 2006

[20] Y. MERY, S. DUCRUIX, P. SCOUFLAIRE, L. VINGERT, C. CRUZ, M. THÉRON, S. CANDEL - *Subcritical and Transcritical Injection under High Amplitude Transverse Acoustic Oscillations*. 3rd EUCASS, Versailles, France, 2009

[21] Y. MERY, S. DUCRUIX, P. SCOUFLAIRE, S. CANDEL - *Injection Coupling with High Amplitude Transverse Modes: Experimentation and Simulation.* Comptes Rendus Mecanique 337 pp. 426-437, 2009

[22] Y. MERY, L. HAKIM, P. SCOUFLAIRE, L. VINGERT, S. DUCRUIX, S. CANDEL - *Experimental Investigation of Cryogenic Flame Dynamics under Transverse Acoustic Modulations*. Comptes Rendus Mecanique 341 pp. 100-109, 2013

[23] A. MURRONE, N. FDIDA, C. LE TOUZE, L. VINGERT - *Atomization of Cryogenic Rocket Engines Coaxial Injectors; Modeling Aspects and Experimental Investigations.* 4th Space Propulsion Conference, Cologne, Germany, 2014

[24] G. ORDONNEAU, H. DOUCHET - *Numerical Simulation of the Vinci Thrust Chamber Ignition.* 4th Int. Conf. on Launcher Technology, Liège, Belgium, 2002

[25] G. ORDONNEAU, P. HERVAT, F. GRISCH, L. VINGERT - *PLIF Investigation of Reactive Flows in the Separation Region of an Over-Expanded Two-Dimensional Nozzle*. 42nd JPC, Sacramento, 2006

[26] G. ORDONNEAU, F. GRISCH, P. HERVAT, P. REIJASSE, L. VINGERT - *Experimental Characterization of Reactive Flows in the Separation Region of an Over-Expanded Two-Dimensional Nozzle*. 6th Int. Conf. on Launcher Technology, Munich; Germany, 2006

[27] G. ORDONNEAU, P. HERVAT, L. VINGERT, S. PETITOT, B. POUFFARY - *First Results of Heat Transfer Measurements in a New Water-Cooled Combustor on the Mascotte Facility.* 4th EUCASS, St Petersburg, Russia, 2011

[28] G. ORDONNEAU, L. VINGERT, N. SLAVINSKAYA, J. SENDER, D. SUSLOV, S. SOLLER, M. ONOFRI, C. BRUNO, D. LENTINI, F. NASUTI, M. VALORANI - *Oxygen-Methane Combustion Studies in In Space Propulsion Program.* 4th EUCASS, St Petersburg, Russia, 2011

[29] S. PETITOT, L. VINGERT, N. FDIDA, P. GRENARD, M. THERON, S. PALERM - *Heat Transfer and GOX&LOX/GH$_2$ Flame Imaging in a High-Pressure and High-Mixture Ratio Rocket Combustor.* 4th Space Propulsion Conference, Cologne, Germany, 2014

[30] M. POUROUCHOTTAMANE, F. DUPOIRIEUX, L. VINGERT, M. HABIBALLAH - *Numerical Analysis of the 10 Bar Mascotte Flow Field.* 2nd International Workshop on Rocket Combustion Modeling, Lampoldshausen, Germany, 2001

[31] F. RICHECOEUR, P. SCOUFLAIRE, S. DUCRUIX, S. CANDEL - *Interactions Between Propellant Jets and Acoustic Modes in Liquid Rocket Engines: Experiments and Simulations*. 42nd JPC, Sacramento, 2006

[32] F. RICHECOEUR, S. DUCRUIX, P. SCOUFLAIRE, S. CANDEL - *High Frequency Ransverse Acoustic Coupling in a Multiple Injector Cryogenic Combustor.* Journal of Propulsion and Power 22 pp. 790-799, 2006

[33] A. ROBLIN, I. DUBOIS, F. GRISCH, A. BOISCHOT, L. VINGERT - *Comparison Between Computations and Measurements of a H_2/LOX Rocket Motor Plume*. 8th Joint Thermophysics and Heat Transfer Conference, St. Louis, Missouri, 2002

[34] B. SAINTE-ROSE, N. BERTIER, S. DECK, F. DUPOIRIEUX - *Numerical Simulations and Physical Analysis of an Over-Expanded Reactive Gas Flow in a Planar Nozzle*. Combustion and Flame, 2012

[35] V. SCHMIDT, D. KLIMENKO, O. HAIDN, M. OSCHWALD, A. NICOLE, G. ORDONNEAU, M. HABIBALLAH - *Experimental Investigation and Modeling of the Ignition Transient of a Coaxial H_2/O_2-Injector.* 5th Int. Conf. on Liquid Rocket, Chattanooga, 2003

[36] T. SCHMITT, Y. MÉRY, M. BOILEAU, S. CANDEL - *Large Eddy Simulation of Oxygen/Methane Flames Under Transcritical Conditions*. Proceedings of the Combustion Institute 33 pp. 1383-1390, 2011

[37] G. SINGLA, P. SCOUFLAIRE, J.C. ROLON, C. CANDEL - *Transcritical Oxygen / Transcritical or Supercritical Methane Combustion*. Proceedings of the Combustion Institute 30 pp. 2921-2928, 2005

[38] G. SINGLA, P. SCOUFLAIRE, C. ROLON, S. CANDEL, S. ZURBACH, J.L. THOMAS - *Experiments and Simulations of LOX/CH_4 Combustion at High Pressures.* 1st EUCASS, Moscow, Russia, 2005

[39] G. SINGLA, P. SCOUFLAIRE, C. ROLON, S. CANDEL - *Planar Laser induced Fluorescence of OH in High Pressure Cryogenic LOX/GH_2 Jet Flames*. Combustion and Flame 144 pp. 151-169, 2006

[40] G. SINGLA, P. SCOUFLAIRE, J.C. ROLON, S. CANDEL, L. VINGERT - *OH PLIF and Emission Imaging in High Pressure Cryogenic LOX/Methane Flames.* Journal of Propulsion and Power 23, pp. 593-602, 2007

[41] G. SINGLA, P. SCOUFLAIRE, C. ROLON, S. CANDEL - *Flame Stabilization in High Pressure LOX/GH_2 and GCH_4 Combustion.* Proceedings of the Combustion Institute, 31 pp. 2215-2222, 2007

[42] L. VINGERT, M. HABIBALLAH, P. VUILLERMOZ, S. ZURBACH - *Mascotte, a Test Facility for Cryogenic Combustion Research at High Pressure*. 51st International Astronautical Congress, Rio de Janeiro. IAF-00-S.3.06, 2000

[43] L. VINGERT, M. HABIBALLAH, P. VUILLERMOZ - *Upgrading of the Mascotte Cryogenic Test Bench to the LOX/Methane Combustion Studies.* 4th Int. Conf. on Launcher Technology, Liège, Belgium, 2002

[44] L. VINGERT, P. GICQUEL, M. BARAT, J. SENDER - *Characterization of Cryogenic Propellants Ignition on the Mascotte Test Rig*. Preliminary Results. 1st EUCASS, Moscow, Russia, 2005

[45] L. VINGERT, P. GRENARD, G. ORDONNEAU, S. PETITOT, S. PALERM - *Improvement of Knowledge and Modelling of Heat Transfer in Cryogenic Combustion Chambers*. 6th EUCASS, Krakow, Poland, 2015

[46] S. ZURBACH, J.L. THOMAS, M. SION, T. KACHLER, L. VINGERT, M. HABIBALLAH - *Recent Advances on LOX/Methane Combustion for Liquid Rocket Engine Injector.* 38th JPC, Indianapolis, 2002

Lucien Vingert graduated from ISAE/Sup'Aéro in Toulouse in 1983. He joined the Energetics Department of ONERA in 1986. He was first involved in atomization studies, mainly related to the coaxial injection elements of the Vulcain engine. From 1990 to 1993, he was also involved in numerical analysis of combustion instabilities, in close contact with the European industry in charge of Ariane's liquid rocket engines.
Since 1993, he has been working on the cryogenic test facility Mascotte, in charge of the successive improvements of the facility and of all the test campaigns, whatever their objectives: combustion efficiency, stability, heat transfer, atomization ...

Gérard Ordonneau is currently the Head of Liquid Propulsion Unit at ONERA, in the Fundamental and Applied Energetics Department. He graduated in Aerospace Engineering (1982) from ISAE/Sup'Aéro in Toulouse. His main interests are the research on combustion instabilities (low and high frequency), ignition and system studies in connection with Ariane's engines development.

Nicolas Fdida graduated from "Ecole Nationale Supérieure de Mécanique et Microtechniques" in Besançon and received his PhD in energetics from the University of Rouen in 2008. He works at ONERA as a research scientist in the Fundamental and Applied Energetics Department, applying various optical diagnostics (Phase Doppler, Laser Induced Fluorescence, high-speed imaging...) to track physical processes of reacting flows. His current research addresses the atomization of two phase flows and the investigation of combustion instabilities.

Philippe Grenard graduated from the French engineer school École Polytechnique and Supaéro. Philippe Grenard is a research engineer working at Onera in the Fundamental and Applied Energetics Departement (DEFA). He is in charge of computational activities regarding the in-house CEDRE platform (modeling, development and computations) in the Liquid Propulsion Unit. His activities focus on combustion and thermal loads in the combustion chamber and nozzle of liquid propellant engines.