

Experimental analysis of a transcritical LOx/CH₄ swirl flame

M. Bouton^{a,b}, A. Nicole^c, N. Fdida^a, S. Boulal^a, L. Vingert^a, M. Theron^b, A. Genot^d, G. Ribert^e

^aDMPE, ONERA, Université Paris Saclay, 91120, Palaiseau, France

^bCNES - Transport spatial - Etablissement de Daumesnil, F-75612 Paris Cedex, France

^cDTIS, ONERA, 13330, Salon-de-Provence, France

^dDMPE, ONERA, Université de Toulouse, 31000, Toulouse, France

^eCORIA - CNRS, Normandie Université, INSA Rouen Normandie, Rouen, 76000, France

1 Introduction

Recent breakthroughs in the space industry have led to the successful recovery of reusable rockets, aimed at reducing space debris associated with launches and contributing to reductions in production costs. These technical achievements have promoted renewed interest in the development of new Liquid Rocket Engines (LRE) and propulsion technologies [1]. Swirl-type injection is an increasingly popular technological solution, improving combustion efficiency and flame stability by introducing rotational motion to the fluid through tangential inlets to promote mixing and atomization [2]. The LOx/CH₄ propellant combination is also gaining popularity and is a good compromise compared with Oxygen/Hydrogen and Oxygen/Kerosen propellants [1]. Combustion instabilities appear to be one of the main concern in the development of LRE injectors [3]. They are triggered by the coupling of hydrodynamic, combustion, and pressure oscillations [4]. This results in high-amplitude and high-frequency mechanical and thermal stresses that can destroy the engine [3]. In order to characterize swirl injectors, it is essential to investigate their dynamics and specifically hydrodynamic instabilities.

Experimental investigations have been carried out to better understand the dynamics of LOx/CH₄ swirl flames under transcritical conditions [5, 6]. They highlight the lack of swirl experimental data for hot-fire and cold-flow experiments regarding LRE, and the limited utilization of intrusive measurements and laser diagnostics because of extreme combustor conditions. The global structure of the LOx/CH₄ transcritical swirl flame was investigated [6] and non-reactive cases highlighted Kelvin-Helmholtz and helical hydrodynamic instabilities in jet dynamics [5]. LOx/CH₄ transcritical swirl flame dynamics still needs to be investigated in depth to address the lack of data for this type of flame.

For this purpose, this work focuses on the behavior of a steady experimental LOx/CH₄ transcritical swirl flame performed on the Mascotte test bench. A single liquid-centered swirl injector is studied to clearly highlight hydrodynamic phenomena and avoid all interaction issues. In the absence of significant pressure oscillations, the interaction between hydrodynamic and combustion dynamics is investigated. First, the experimental configuration is presented. The flow dynamics are then analyzed through spectral analysis of non-intrusive measurements, before the conclusion and upcoming elements to complete this paper.

2 Experimental configuration

The cryogenic Mascotte test bench from ONERA is a well-known experimental facility used for exploring cryogenic combustion [7, 8]. The *Bhp-Hrm*¹ combustion chamber (co-funded by ONERA and CNES) used to perform these experiments is designed for operating at high pressure with a high mixture ratio. It is described in Fig. 1a. The combustor was used for several experimental campaigns [7]. The injector is made up of two concentric tubes. Methane is injected through the outer tube in a straight flow. The central tube is the swirl LOx injector, where the rotational motion is induced by four tangential inlets.

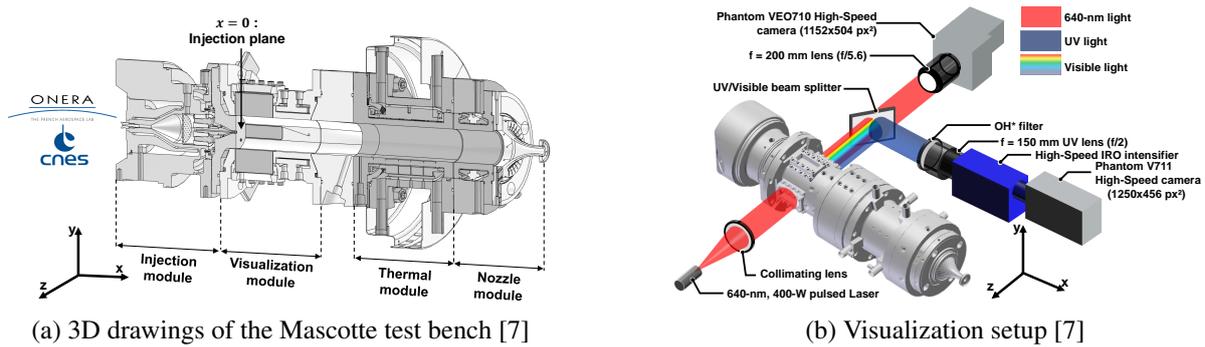


Figure 1: Experimental setup

The operating point aims to replicate the nominal combustion chamber operating conditions of the Prometheus engine -100 bar with a mixture ratio of 3.5- within the limits allowed by the test bench [9]. The Mascotte combustion chamber mean pressure is therefore 62 bar. The flow condition values are time-averaged during the recording time camera whose duration is 1.5 s. A single operating condition is performed under transcritical conditions with respect to the thermodynamic oxygen critical values ($P_c^{O_2}=5.042$ MPa, $T_c^{O_2}=154.5$ K). LOx is injected above its critical pressure but below its critical temperature. Methane is injected above its critical pressure and temperature ($P_c^{CH_4}=4.599$ MPa, $T_c^{CH_4}=190.6$ K), thus in a supercritical state. The mixture ratio, defined as $MR = \dot{m}_{LOx}/\dot{m}_{CH_4}$, is 4.3. It indicates a slightly oxidizer-rich combustion. This value lies close to the stoichiometric mixture ratio of 4 for LOx/CH₄ combustion (global equivalence ratio about 0.93), highlighting that the mixture is near stoichiometric conditions and ensuring high temperature conditions at chemical equilibrium.

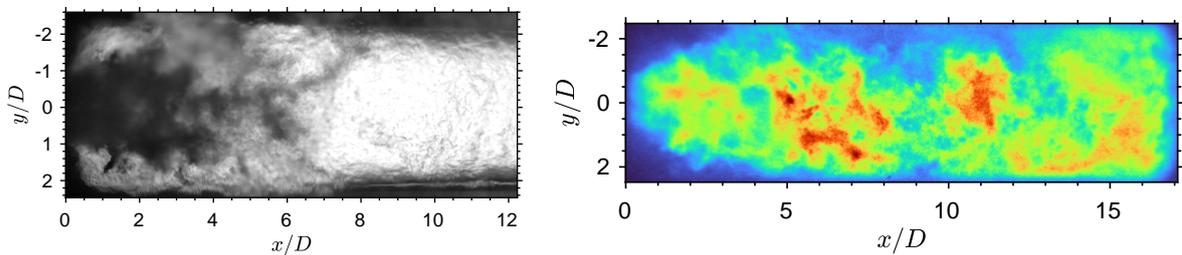


Figure 2: Instantaneous captures of high-speed visualizations

¹Boîtier Haute Pression et Haut Rapport de Mélange

Four optical accesses enable visualization measurements in the injector plane vicinity. Backlighting and OH* chemiluminescence high-speed visualization measurements are used in this study, as they are the main available tools to describe such a high pressure cryogenic flame [10]. The experimental setup presented in Fig. 1b is the same as operated by Boulal et al. [7]. Backlighting (Fig. 2a) is used to visualize shading effects created by dense phase illumination with a collimated light beam, where strong density gradients between the dense and the light phases induce light beams deviation [10]. OH* chemiluminescence (Fig. 2b) allows to observe radiations emitted by OH radical in the reaction zone [7]. They are line-of-sight integrated quantities. OH* is used as an indicator of the volumetric heat release rate which is fundamental to study combustion instabilities. Cameras are time-synchronized and operate at a 13 kHz acquisition rate.

3 Results

3.1 Backlighting

To investigate the destabilization and dynamics of the dense jet surface using backlighting (Fig. 2a), a spectral analysis using the Fast Fourier Transform (FFT) is conducted in a zone close to the injector vicinity within $x/D < 4.5$ (Fig. 3a). D refers to the LOx injector diameter. The aim is to identify coherent motions in an a priori chaotic flow. In Fig. 3a, a significant peak is observed at 3422 Hz. Filtering the video with an Inverse Discrete Fourier Transform (IDFT) at this frequency gives the shape of the mode. Mode shape is given in Fig. 3b. This shows that it is associated to a symmetric mode, as blue and red wave packets alternatively appear on both sides of the injector axis, along the interface between the dense and the light phases. No coherent structures are visible in the middle of the image along $y/D = 0$ as the light beams blocked by the dense phase do not reach the camera. Structures are the most intense at $x/D = 2.5$ and decrease in intensity after $x/D = 3$ due to vaporization and shear forces. Wave packets are related to coherent ring annular vortices structures [5]. Ring vortices are shed from the exit plane ($x/D = 0$) and the injectors lips ($y/D = \pm 1$). Then, they develop downstream and destabilize the LOx jet as their size increases through vortex pairing [11]. These features are the signature of a Kelvin-Helmholtz instability [5].

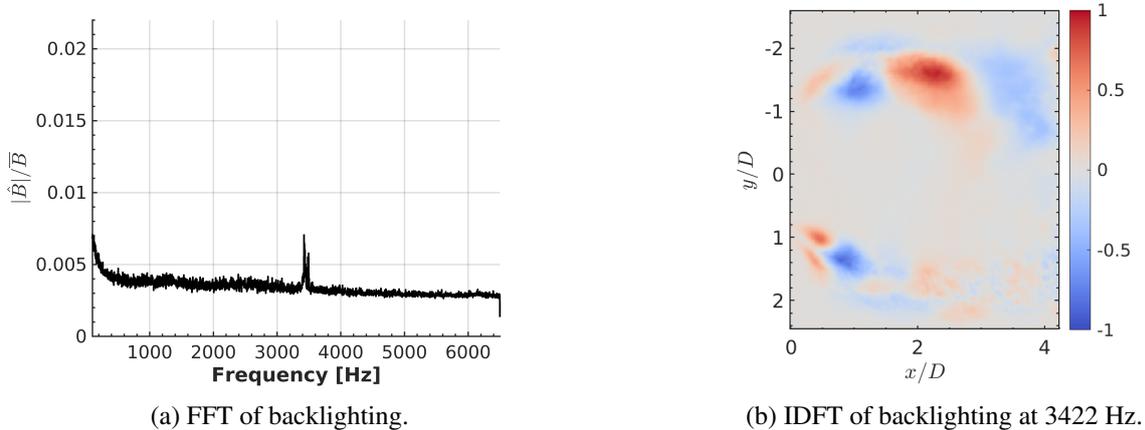


Figure 3: Spectral analysis of backlighting close to the injection plane vicinity.

The Strouhal number associated with this frequency is $St = fR/U = 0.5$, scaling the mode frequency by the radius R of the LOx injector and U the LOx film bulk velocity within the injector [12]. The

Strouhal value lies within the literature interval 0.25 – 0.5, referring to the jet preferred mode, i.e., the most unstable frequency of an axisymmetric jet [13]. This Strouhal number is also retrieved in other numerical and experimental cold-flow studies using similar swirl injector configurations [5, 12]. R is chosen as the characteristic length because it corresponds to the total LOx discharge length at the injector exit [12].

3.2 OH* chemiluminescence

The instantaneous OH* field capture given in Fig. 2b shows that OH radical is spontaneously excited in almost the entire visualization zone. Under high pressure and temperature conditions, thermal excitation is the primary mechanism responsible for the OH radical excitation in H₂ flames [14, 15]. In this work, for LOx/CH₄ combustion, operating at a mixture ratio close to the stoichiometric value ensures high temperatures [16] in the same range of Fiala et al. [15], above 2500 K. Additionally, stoichiometry ensures the presence of OH radical at thermal equilibrium, able to be excited downstream within the hot gases, even in the absence of ongoing chemical reactions. Therefore, it can be inferred that under the high pressure and temperature operating conditions, OH* excitation, for this case, mostly lies on the thermal excitation mechanism. OH* concentration also exhibits an exponential dependency to temperature [15]. However, temperature difference between the flame reaction zone and burnt gases refreshed with unburnt oxygen still allows the reaction zone to be distinguished. OH*, in this case, is still a good marker of the reaction zone. But under these conditions, estimating the flame length remains challenging. Even if OH* and heat release rate comparison can then present spatial differences, Hardi et al. [14] showed that their time signals can be similar.

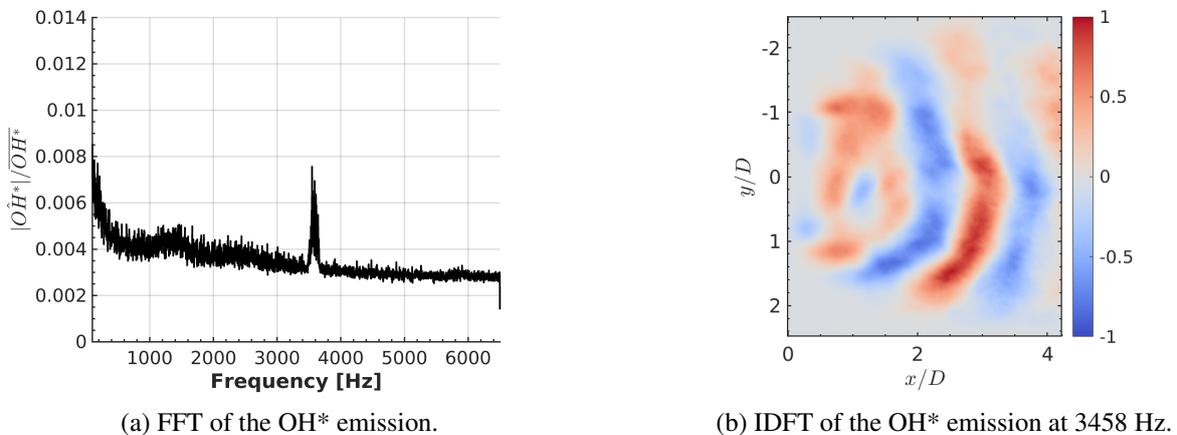


Figure 4: Spectral analysis of OH* emission close to the injection plane vicinity

To evaluate OH* dynamics, a spectral analysis is conducted in the same zone than backlighting with an FFT (Fig. 4a). A dominant frequency is visible at 3548 Hz. This frequency is also close to the Strouhal number $St = 0.5$. A filtering through IDFT is performed in Fig. 4b to obtain the corresponding mode shape. It appears to be a symmetric mode again, associated to a Kelvin-Helmholtz instability as ring-shaped waves propagate downstream and follow the flame opening angle [5]. However, contrary to backlighting, structures do not seem to lose their energy at $x/D > 3$. The signal is also visible, this time, in the middle of the image along $y/D = 0$. This can be explained by the difference in the visualization techniques used. OH* emits radiations throughout reaction zone, whereas in backlighting, the dense phase obstructs light transmission. Accounting for all these considerations regarding frequencies and mode shapes, it can be inferred that the same mode is observed by the two time-synchronized high-speed

cameras. In the absence of significant pressure oscillations in the combustion chamber, which will be evidenced in the full paper, it can be guessed that OH* dynamics would be driven by the dense phase dynamics within the reaction zone. Namely, a coherent wave structure at the surface of the LOx jet can drag methane deeper in it, resulting in mixing layers fluctuations emphasized by combustion fluctuations visible via OH* emissions.

4 Conclusion

A single liquid-centered LOx/CH₄ swirl element is investigated in representative conditions of a Liquid Rocket Engine combustor on the cryogenic MASCOTTE test bench from ONERA. Two high-temporal-resolution measurements are carried out to observe the dense phase and flame dynamics under a stable operation.

Backlighting is used in order to observe the dense phase dynamics. OH* chemiluminescence is used as an indicator of the reaction zone. The most energetic mode associated to a symmetric coherent vortex ring structure is evidenced through spectral analysis in the two visualization tools. These features are the signature of a Kelvin-Helmholtz instability which is, in this case, related to the most amplified frequency of the LOx jet ($St = 0.5$). This corresponds to a typical Strouhal number found for similar non-reactive cases. Consequently, it can be inferred that reaction zone dynamics are primarily driven by the dense phase dynamics. OH* visualization have also shown that high temperature in the combustor can be able to predominantly excite the OH radical even without ongoing chemical reactions. This limits the reliability of comparisons between the heat release rate and highlights the need for alternative comparison methods. OH* exponential dependence to temperature could be a first insight for validation of a numerical analysis.

All these results feed the experimental database on transcritical swirl liquid-centered LOx/CH₄ flames on the established Mascotte test bench. In the upcoming presentation and full paper, additional information will be provided on the pressure and instantaneous and mean fields, as well as the spectral analysis process. Finally, for a better understanding of flame dynamics, a numerical simulation (LES) of the operating point is running to gain more information about this type of flame. Also, more detailed spectral analysis tools as POD or DMD could be used.

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