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Sebastian Milu-Vaidesegan, Mikael Orain, Pierre Doublet, Marc Bellenoue. Study of flame-wall interaction: influence of effusion cooling on pollutant emissions. 20th International Symposium on Applications of Laser and Imaging Techniques to Fluid Mechanics, Jul 2022, Lisbonne, Portugal. hal-03745426

**HAL Id: hal-03745426**

**<https://hal.science/hal-03745426>**

Submitted on 4 Aug 2022

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# Study of flame-wall interaction: influence of effusion cooling on pollutant emissions

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**Keywords:** Pollutant emissions, OH-PLIF, Flame-wall interaction, Effusion cooling

## ABSTRACT

For several years, engine manufacturers have had to meet increasingly stringent standards on pollutant emissions. Studying the flame-wall interaction is essential to control pollutant emissions and extend the lifetime of gas turbine. An inherent constraint of combustion chambers is that the walls are cooled by air introduced through multi-perforation (effusion cooling). The problem is that this injection of cold air into the combustion chamber disrupts the oxidation reactions of the fuel either by freezing them, which yields the emission of large quantities of CO, UHC and soot or by bringing fresh air to the rich areas, which is favourable to the formation of  $NO_x$ . The focus of this work is to investigate the influence of parameters such as burner flow rate, cooling flow rate and equivalence ratio on the reaction zone. Experiments were conducted with a multi-perforated plate placed above a flat flame burner to simulate the head-on interaction between an aeronautical injector and an effusion cooled liner. Results show that for rich mixtures, a partially-premixed flame front is formed 3 to 8 mm from the cooled plate. By increasing the fresh gases flow rate, the flame widens horizontally because of the expansion of hot gases that are unable to convect upwards due to the presence of the plate. The close-up images recorded show the formation of a series of parallel flamelets in the vicinity of the cooled plate which indicates the ongoing oxidation of the remaining fuel in the burnt gases while mixing with the cooling air jets.

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## 1. Introduction

For several years, the aeronautical sector has had to face the problems of increasing air traffic, the reduction of pollutant emissions and climate change (Lefebvre & Ballal, 2010). In this context, engine manufacturers have had to concentrate their efforts on designing engines with lower fuel consumption and meet increasingly stringent standards on pollutant emissions. Among the pollutants emitted during combustion, nitrogen oxides ( $NO_x$ ), carbon monoxide ( $CO$ ) and particulate matter ( $PM$ ) are considered to have a negative influence on health, and carbon dioxide is known as a greenhouse gas. A special effort must be made to reduce the amount of those pollutant released in the atmosphere. For that reason, it is necessary to understand and be able to model their formation in order to optimize combustion efficiency.

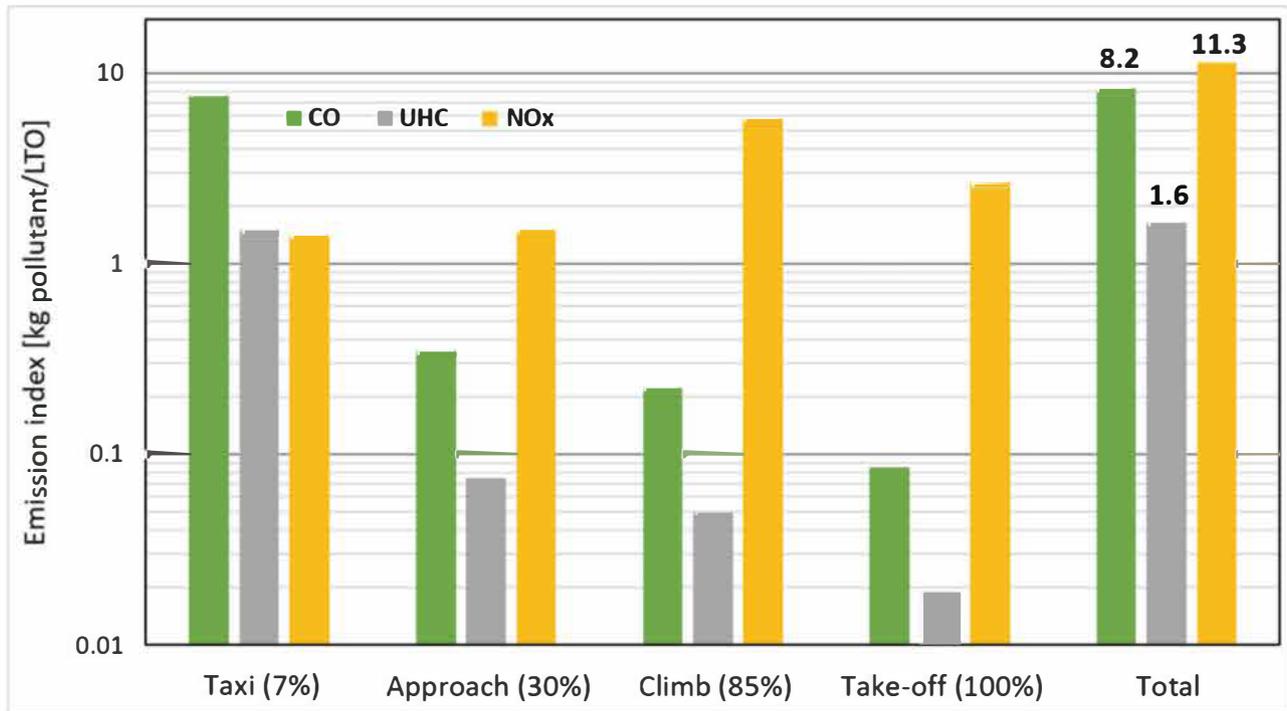


Figure 1: Emissions index of an Airbus A320 powered by twin CFM56 – 5B engines during different stages of the standard LTO cycle. In parenthesis, the engine thrust percentage. (1.A.3.a Aviation 2 LTO Emissions Calculator 2019 – European Environment Agency, n.d.)

An inherent constraint of combustion chambers is that the walls are generally cooled by air introduced either as films along the combustion liner or through multi-perforation (effusion cooling), thus extending the lifetime of the engines. The problem is that this injection of cold air into the combustion chamber disrupts the oxidation reactions of the fuel:

- either by freezing them, which yields the emission of large quantities of  $CO$ ,  $UHC$  (unburned hydrocarbons) and soot;
- or by bringing fresh air to the rich areas, which has the consequence of lowering the equivalence ratio close to stoichiometry which, in turn, is very favourable to the formation of thermal  $NO_x$ .

Understanding the physical mechanisms linked to the formation of pollutants in flames is a crucial point for improving aeronautical combustion chamber technologies, as well as the predictability of numerical simulations and their associated models. In addition, studying the flame/wall interaction is essential for engine manufacturers in order to control pollutant emissions and extend the lifetime of gas turbine. However, making these improvements, whether technological or digital, is based on the ability to obtain prior information, quantitative if possible, on the physical parameters of the flows considered.

Optical diagnostics are well suited to perform in-situ measurements in combustion chamber and have been developed and applied over the years. Lange et al. (Lange et al., 2012) used simultaneous planar laser-based techniques in reactive flow within a high-pressure single sector combustor. They studied the interaction between a premixed lean flame and the near wall cooling film at a pressure of 5 bars and preheat air temperature of 450 K. For this purpose different measurement techniques were used such as the planar laser-induced fluorescence (PLIF) of the OH radical to study the mixing properties of combustor flow and film cooling as well as particle image velocimetry (PIV) to visualize and quantify the recirculating flow field. From a diagnostic point of view, the feasibility of such combinatory measurements was successfully demonstrated. Close-up views of the reacting flow revealed small air jets issuing from holes in the effusion cooled liner wall. However, at wall distances of less than 2 mm the reflection of the emitted OH light by the wall reduces the reliability of the OH concentration estimates. More recently, Voigt et al. (Voigt et al., 2017) used the same experimental test rig operated with a mixture of air and natural gas to measure the distribution of the CO concentration by planar laser-induced fluorescence. OH-PLIF was equally applied to measure the OH concentration from which the authors deduced the temperature distribution. This measurement allowed to correct the CO-PLIF signal and provide quantitative measurements of the CO concentration at different locations along the flame front. The goal was to further improve the knowledge on the CO distribution as an intermediate combustion product in order to better understand the influence of cooling air on combustion. The authors concluded that in the recirculation zone, where measurable quantities of CO were found, oxidation was slowed down almost to a stop due to the low temperature of the combustion gases diluted with cooling air. Jainsky et al. (Jainski et al., 2017) studied the flame-wall interaction of laminar premixed methane-air flames at atmospheric pressure by using various laser diagnostic methods. Velocity fields and flame front locations were measured simultaneously by two-component PIV and OH-PLIF. Coherent anti-Stokes Raman Scattering (CARS) and two-photon CO-PLIF were used to determine temperatures and CO concentrations. The flame-wall interactions process was investigated using an air/methane generic burner setup where one branch of a V-shaped flame interacted with a water-cooled stainless steel wall, corresponding to a sidewall quenching (SWQ) geometry. Flame-wall interaction was studied for equivalence ratios of  $\phi = 0.83, 1.0$  and  $1.2$ . The quenching distance of the flames was determined from the results of the OH-PLIF measurement. Depending on the equivalence ratio, it was found that the quenching distances varied from  $\approx 250$  to  $400 \mu\text{m}$  and negatively correlated to the laminar flame speed. Approaching the flame-wall interaction zone and close to the wall, gas temperatures and wall-normal temperature gradients increased. This was accompanied by increased heat losses. Simultaneously, the zone of peak CO

concentrations shifted towards the wall. Greifenstein et al. (Greifenstein et al., 2018) investigated the flame-cooling air interaction by means of wall temperature (2D thermographic phosphor thermometry), gas phase temperature (CARS), flame structure (OH-PLIF) and flow field (PIV) measurements in an effusion-cooled single sector model gas turbine combustor. The test bench was operated under close-to-reality conditions with elevated combustor inlet temperature and increased system pressure. Parametric variations of parameters such as swirl and effusion cooling air mass flow were conducted to investigate their effect on total film cooling effectiveness. Peak wall temperature varied up to 150 K across all parametric variations and up to 200 K in axial direction on the effusion-cooled liner for a given condition. Tremendous variations of total cooling effectiveness between 10 and 34 % from the flame-cooling air interaction zone to the post flame area were observed.

The literature survey shows that OH-PLIF is one of the most relevant techniques to conduct flame-wall interaction studies. This measurement can either be used to identify the reaction zone and therefore to measure the flame quenching distance or to deduce the flow temperature from the quantitative OH concentration, allowing thus to correct further species fluorescence measurements (i.e. CO-PLIF). However, previous works have focus on the sidewall quenching which occurs in conventional annular combustion chambers where the fuel injection axis is parallel to the airflow. Nevertheless, some gas turbines manufacturers chose to deviate from this rule in an attempt to further reduce engine size and therefore operational cost for customer. In this case, the fuel injection is done towards the effusion cooled liner and the flame-wall interaction occurs heads-on.

This work focuses more specifically on the effect of the flame/wall interaction on the reaction zone. The objective is to characterize the influence of certain parameters such as equivalence ratio and secondary air flow on the flame front and its spatial distribution near a multi-perforated wall. Planar laser-induced fluorescence (PLIF) imaging applied to the OH radical has been used. Experiments were carried out on a flat flame burner which allowed us to define the best laser excitation strategies and the most suitable spectral domains of fluorescence collection, to calibrate the technique and also to tackle the issues with near-wall measurements. The OH radical concentration increases significantly in the reaction zone, as a result, the position of the flame front can be extracted from OH-PLIF images by means of gradients and filtering techniques.

## 2. Material and methods

### a. Experimental test rig

The experimental test rig is made up of a water-cooled flat flame burner (from Holthuis & Associates) designed for a methane/air mixture. Before reaching the reaction zone, the fresh gases travel through a porous media which provides an equal distribution of the fuel/oxidizer mixture over the entire burner surface at low velocities, leading to a very stable laminar flame. This burner is equally provided with a centre hole allowing the user to inject a secondary fuel at the centre of the reaction zone and observe its influence on pollutant emissions or flame instabilities. However, during present experiments, this centre tube was plugged to prevent any air suction from below.

A multi-perforated plate with 365 holes of 0.4 mm diameter perforated in staggered rows is placed above the burner (**Figure 2b**). The plate is manufactured using a highly thermally resistant nickel-chromium-molybdenum aerospace grade alloy. A basket is designed around the plate to allow the injection of cooling air. A K-type thermocouple is welded inside the basket at the centre of the multi-perforated plate in order to track the variations of wall temperature during experiments. The entire basket is supported by threaded rods allowing to adjust easily and accurately the distance between the perforated plate and the base of the burner (**Figure 2b**).

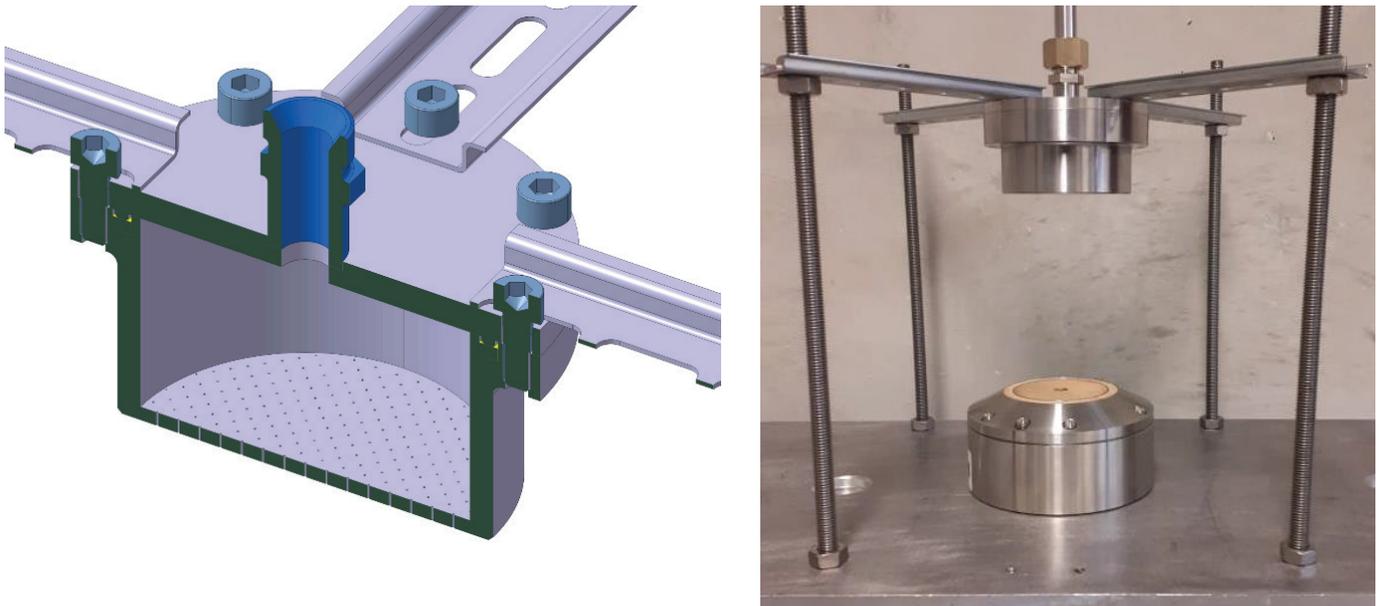


Figure 2: (a) 3D design of the multi-perforated plate and its support;  
(b) multi-perforated plate placed above the flat flame burner.

The flowrates of the different gas (methane and air combustion, multi-perforation air) are monitored and regulated by mass flow controllers (EL-FLOW Prestige and EL-FLOW Select

from Bronkhorst). The methane flow is limited to 5 Ln/min, the burner air flow can reach 50 Ln/min and the cooling air flow has a capacity up to 100 Ln/min. Downstream from the controllers a tee union connector is used to mix homogeneously the fuel and the oxidizer before being injected into the burner plenum.

### **b. Spectroscopic background**

Measurements near a multi-perforated wall require the use of a non-intrusive technique in order to avoid the disturbance of the flow. Additionally, the technique needs to be selective, so as to probe a single species. Laser-induced fluorescence is a very suitable method for detecting OH molecules in a chemically reactive flow and has therefore been extensively used over the years. This method relies on the excitation of molecules through the absorption of photons generated by a laser source which is tuned to a wavelength specific of the energy levels of the molecules. Once excited, molecules will seek to return to their ground energy state by releasing some of their excess energy in the form of light, which is called fluorescence. In the case of OH radical, excitation at about 283 nm and collection around 310 nm is typically used (Bresson, 2000).

### **c. OH-PLIF setup**

In the present experiments, a Nd:YAG laser (Quantel YG981C) at 532 nm (energy: 350 mJ, repetition rate: 10 Hz) is used for pumping a tuneable dye laser (Quantel TDL+). The pulse duration is 8-10 ns. The dye solution used is a mixture of rhodamine 590 & ethanol with rhodamine 610 & ethanol. The dye beam at 566 nm is then frequency-doubled in a crystal to provide a 283 nm beam which is separated from the residue at 532 nm by a Pellin-Broca prism. The energy at 283 nm measured at the output is 16 mJ with good pulse-to-pulse stability. The absolute wavelength of the dye laser is determined using a wavelength meter (WS6 from HighFinesse) before each experiment. In the present experiment, the laser wavelength is tuned to 282.75 nm which corresponds to  $A^2 \Sigma^+ (v' = 0) - X^2 \Pi (v'' = 1)$  transition of OH radical. The laser beam of 6 mm diameter is transformed into a thin light sheet by using a set of cylindrical lenses and a spherical lens. This results in a light sheet of roughly 50 mm width and 500  $\mu\text{m}$  waist with a maximum power density of 1 MW/cm<sup>2</sup>.

OH fluorescence signal is collected by a lens (Cercu-UV 100 F/2.8 from Sodern) and recorded by means of an ICCD camera (PI MAX4 from Teledyne Princeton Instruments) equipped with a GEN II intensifier optimized for UV light, with a resolution of 1024  $\times$  1024 pixels<sup>2</sup>. The gate of the intensifier is equal to 100 ns. A combination of a longpass filter (ZUL300 from Asahi Spectra, transmission rate > 90%) and a bandpass filter centred at 310 nm

(ZBPA310 from Asahi Spectra, transmission, FWHM=8 nm, 60% transmission rate) is used to isolate spectrally the fluorescence from OH radical. The camera's trigger is synchronized with the pump laser's Q-switch signal and the acquisition rate is 10 images/s.

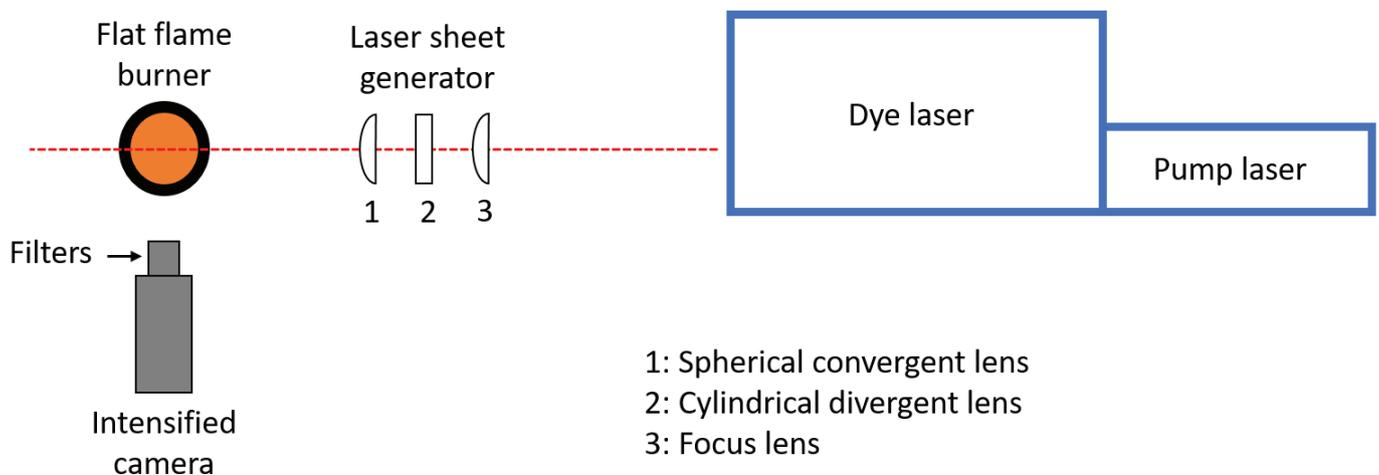


Figure 3: Experimental set-up for OH-PLIF measurements.

#### d. Operating conditions used in the experiments

In order to exploit the full range of the flow controllers, experiments are conducted with methane flowrates between 1 and 5 Ln/min and air flowrates between 10 and 25 Ln/min, leading to an equivalence ratio varying from 0.6 (lower flammability limit) to 2 (highly rich mixture). In order to limit the temperature at the centre of the multi-perforated plate around 300 °C, a cooling air flowrate of 10 to 25 Ln/min is imposed.

Although direct visualizations are conducted on the entire equivalence ratio range, PLIF measurements are mainly focused on rich mixtures where the most relevant interactions with the multi-perforated plate are expected to be found.

### 3. Results

#### a. Direct visualizations

Direct visualizations of the flat flame are performed with a coloured IDS uEye camera with a resolution of  $528 \times 1134$  pixels<sup>2</sup> at different equivalence ratios and air flowrates (Figure 4). As expected, the higher the fresh gases flowrate is, the higher the flame front becomes. For rich mixtures, a bright green secondary flame front appears due to the chemiluminescence emission from C2\* radical.

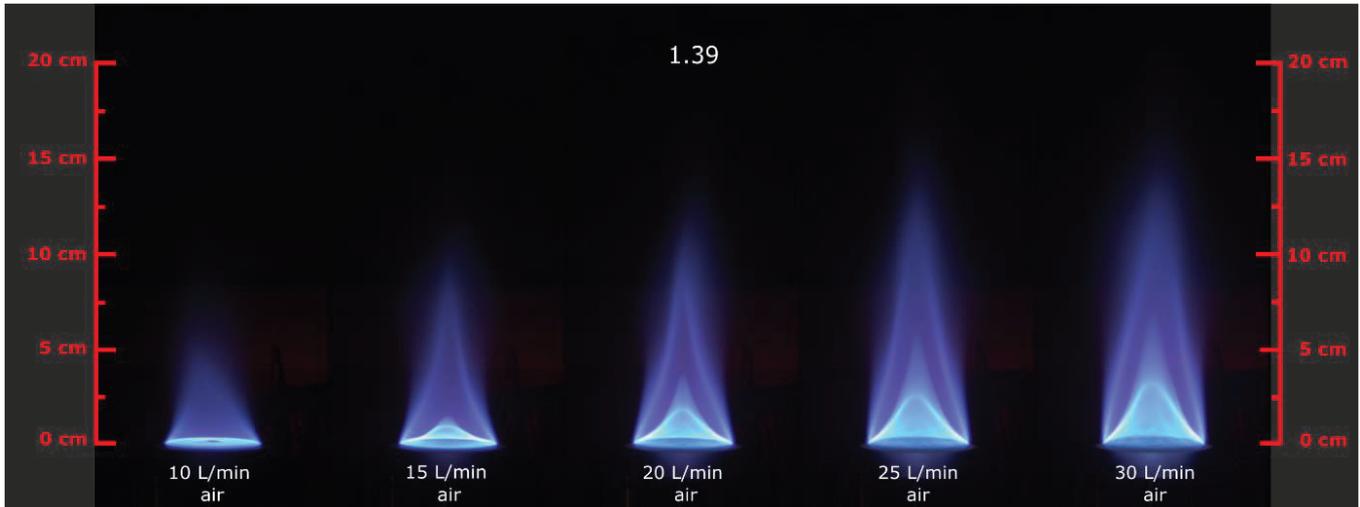


Figure 4: Flame height evolution as a function of oxidizer flowrate for an equivalence ratio  $\phi = 1.39$ .

### b. OH-PLIF without multi-perforated plate

In order to characterize the flat flame front, OH-PLIF qualitative measurements are performed for a number of air flowrates and different equivalence ratios. It can be seen in Figure 5, that up to stoichiometry, the premixed flame front is stabilised at the base of the burner while in the rich domain, a conical partially premixed flame front appears on the outer edges of the burner. A secondary flame front is equally seen at  $\phi = 1.4$  although the OH fluorescence signal is much weaker. The maximum signal is obtained for the richest mixture at  $\phi = 1.6$ . For lower equivalence ratios, the influence of the burner's centre hole is clearly visible due to the lack of OH-PLIF signal.

### c. OH-PLIF with multi-perforated plate

Experiments are conducted by placing the multi-perforated plate at 100 mm above the burner (Figure 6). The recorded images show that for low cooling air flowrates ( $\leq 15$  L/min), the plate can be cooled efficiently (wall temperature remains constant between 200 – 250 °C) without disturbing the flame. A maximum OH fluorescence signal is reached between  $\phi = 1.7 - 1.8$ . When the cooling air flowrate increases, the flame is dynamically quenched at the base of the burner.

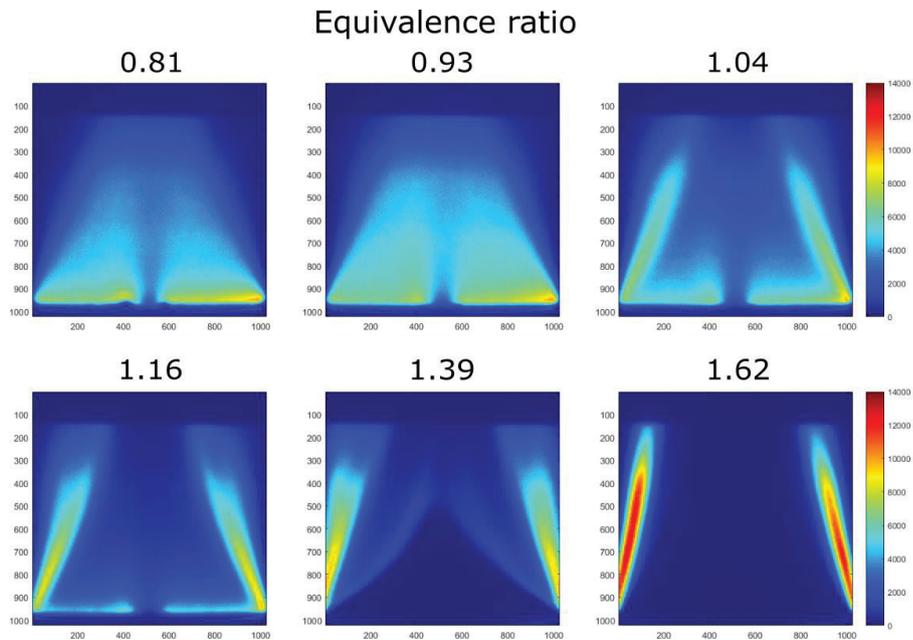


Figure 5: Averaged image of OH-PLIF signal in a simple burner configuration (without the multi-perforated plate) as a function of equivalence ratio with a 25 Ln/min air flowrate. The laser sheet propagates from right to left.

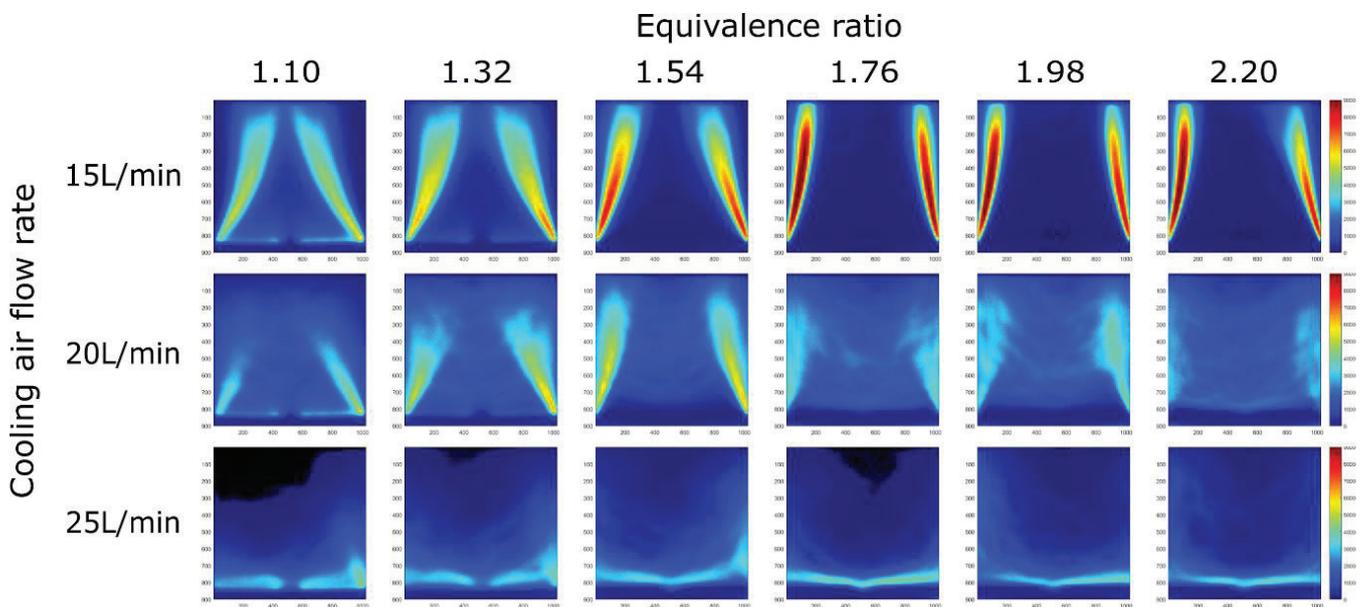


Figure 6: OH-PLIF measurements with the multi-perforated plate placed 100 mm above the burner, as a function of the cooling air flowrate. Burner air flowrate is 15 Ln/min. Dark patches corresponds to null pixel values resulting from background signal subtraction during image post-processing. The laser sheet propagates from right to left.

In a second series of experiments, the multi-perforated plate was placed 45 mm above the burner surface. The goal was to ensure that the laser sheet could cover the entire zone between

the two modules. The secondary air flow rate was carefully adjusted so that the perforated plate would remain at a low temperature (between 200 and 300 °C) without dynamically quenching the flame at the base of the burner as seen previously (Figure 7).

For a given air-cooling flow rate, it can be seen that increasing the equivalence ratio has a significant impact on the shape of the flame front. For lean mixtures, the same evolution as before can be noticed with the transition from a horizontal fully premixed flame to a slightly conical partially premixed flame starting at stoichiometry. However, for rich mixtures, a secondary flame front appears a few millimetres from the surface of the perforated plate. In this case, the excess fuel in the fresh gases burns with the air arriving from above. Looking at the injection axis, it can be noticed that the secondary front bends downwards because of the lack of fresh reactants coming from below (due to the plugging of the burner centre hole). Therefore, the incoming cooling air pushes the flame front further away from the plate at this position.

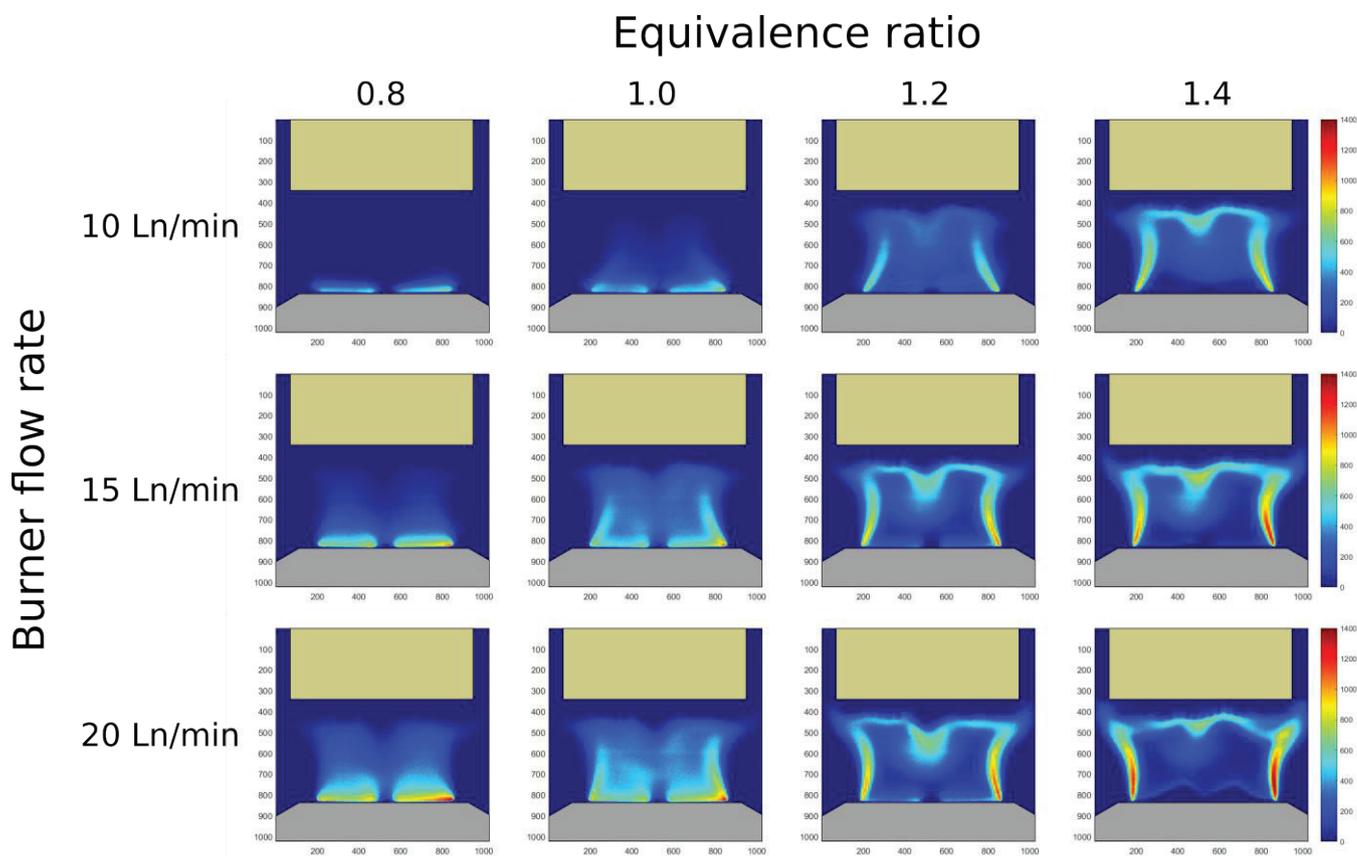


Figure 7: OH-PLIF measurements for different equivalence ratios and fresh gases flow rates, with the perforated plate located at 45 mm above the burner. The observed field is of 75 mm × 75 mm. The cooling air flow rate is 15 Ln/min. The laser sheet of 48 mm propagates from right to left. The shapes represent: on top the perforated plate with its basket; on the bottom the burner edges.

For a given equivalence ratio, the increase of the fresh gases flow rate increases the OH-PLIF signal which indicates that the reaction rate across the flame front increases. As such, for all equivalence ratio, the highest signal is obtained for a fresh gases flow rate of 20 Ln/min.

Furthermore, by plotting the contour of the flame (Figure 8), it appears that the flame widens as the flow rate across the burner increases. This was expected because of the increase of fresh gases velocity at the exit of the sintered frit. The presence of the cooling basket equally influences the widening of the flame by reducing in the vertical direction the volume available for the hot gases to expand.

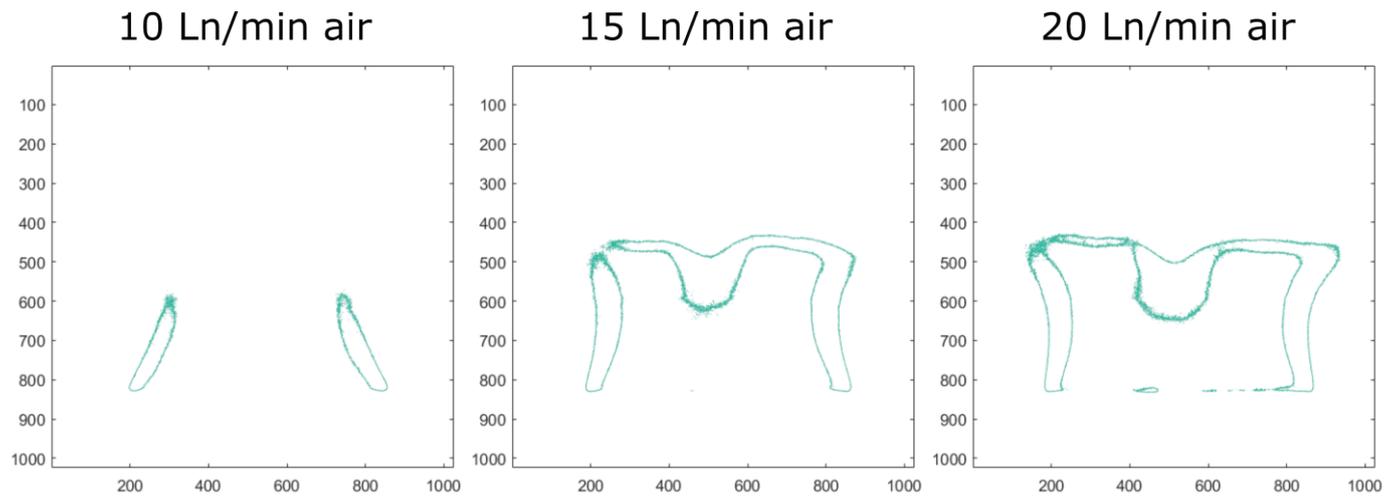


Figure 8: OH-PLIF signal contours as a function of the fresh gases flow rate for an equivalence ratio of  $\phi = 1.2$  and a cooling flow rate of 15 Ln/min.

By recording close-up images of the flame-wall interaction, multiple vertical flamelets can be spotted which correspond to rows of holes perforated on the plate placed above (Figure 9). This phenomenon indicates that the combustion gases that cross the partially premixed flame front near the wall, are still rich enough to keep oxidizing when they mix with the air cooling jets coming from above.

A parametric study of the flame/wall distance was made as a function of the fresh gases flow rate and the mixture equivalence ratio (Figure 10). This distance was measured between the cooled plate and the frontier between combustion products and cooling air. Knowing that the laser energy was stable during experiments ( $\pm 5\%$ ), the frontier was determined from the PLIF-OH measurement by plotting the contour for a signal-to-noise ratio of 2. Results show that the flame/wall distance varies between 3 to 8 mm, the highest values being measured at low equivalence ratios and flow rate (i.e. 10 Ln/min and  $\phi = 1.2$ ).

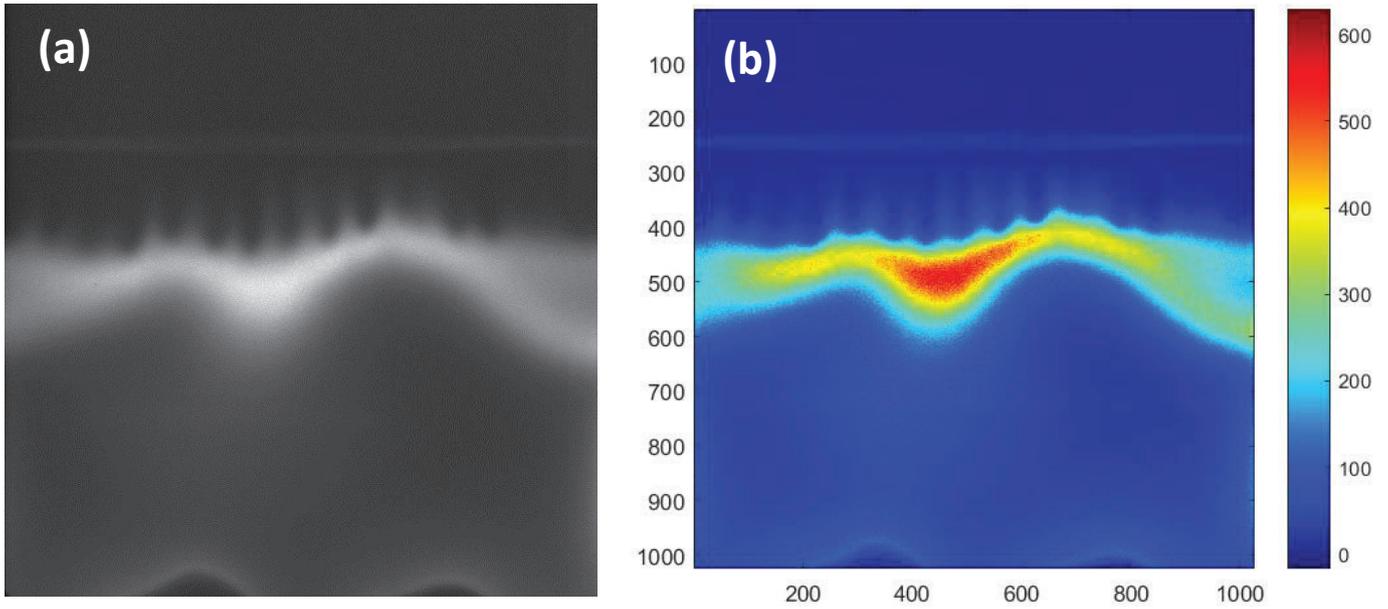


Figure 9: (a) Average image from a batch of 700 instantaneous OH-PLIF images; (b) background corrected average OH-PLIF image with colour scale. The field of view dimensions are  $42\text{ mm} \times 42\text{ mm}$ .

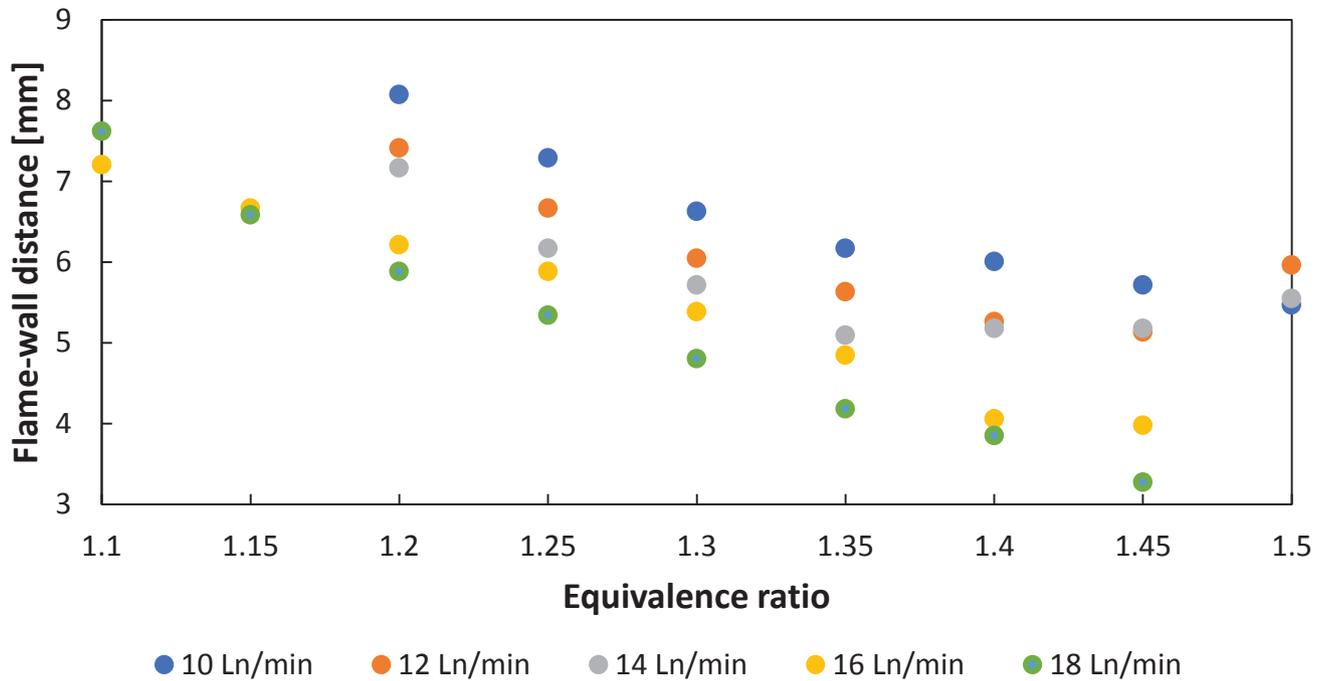


Figure 10: Flame/wall distance as a function of burner flow rate and equivalence ratio. The cooling flow rate is 15 Ln/min.

#### 4. Conclusion and perspectives

Experiments were conducted with a multi-perforated plate placed above a flat flame burner to simulate the head-on interaction between an aeronautical injector and an effusion cooled liner. OH-PLIF measurements were performed across a wide range of conditions to characterize the influence of key parameters such as burner flow rate, cooling flow rate and equivalence ratio. Results show that for rich mixtures, a partially-premixed flame front is formed 3 to 8 mm from the cooled plate while the latter is kept at a stable temperature of around 300 °C. By increasing the fresh gases flow rate, it can be noticed that the oxidation rate increases and the flame widens horizontally because of the expansion of hot gases that are unable to convect upwards due to the presence of the basket above. The close-up images recorded show the formation of a series of parallel flamelets in the vicinity of the cooled plate which indicates the ongoing oxidation of the remaining fuel in the burnt gases while mixing with the cooling air jets.

The next phase of our work is to develop a near-wall CO-PLIF technique on the flat flame burner and to adapt the post-processing algorithm to obtain realistic quantitative results by taking into account absorption, quenching, photoionization rates and spectral overlapping. Replacing methane with other used fuels such as propane is also a possibility that will be investigated. The results will be used to identify the parameters influencing the production of pollutants, as well as to propose new strategies to reduce emissions in order to meet future pollution standards.

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