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Author(s):

Miniero, Luigi ; Pandey, Khushboo; Shcherbanev, Serge ; Doll, Ulrich; Noiray, Nicolas

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Tomographic Reconstruction of OH Density Maps for Jet-A1 Spray Flame in a Vitiated Crossflow

Luigi Miniero^a, Khushboo Pandey^a, Sergey Shcherbanev^a, Ulrich Doll^b, Nicolas Noiray^{*,a}

^a*CAPS Laboratory, Department of Mechanical and Process Engineering, ETH Zürich, Switzerland*

^b*Paul Scherrer Institute, Experimental Thermal-Hydraulics Group, Forschungstrasse 111, CH-5232 Villigen PSI, Switzerland*

Abstract

This paper aims at describing the effects of the variation of air-to-liquid ratio (ALR) on the morphology, reaction zone and combustion regime of a Jet A-1 spray flame in a vitiated turbulent crossflow. The variation of these characteristics as a function of the ALR is a result of the effect of the parameter on both the droplets size and jet-to-crossflow momentum ratio. At low ALR, the spray is characterised by larger droplets and weaker crossflow entrainment. The large-inertia droplets tend not to follow the air jet and penetrate independently in the vitiated crossflow, where they burn in a single droplet combustion regime. On the other hand, the better atomisation and the high fuel-oxidisers mixture obtained through crossflow entrainment favour the formation of a MILD combustion regime. The experimental investigation is performed by means of OH* chemiluminescence and a discrete tomographic reconstruction of the OH- and Jet A-1 Planar laser induced fluorescence of the reaction zone.

1. Introduction

In recent years, the growing awareness of the adverse effects on the environment and human health caused by combustion-related pollutant emissions has led governments and organizations to promulgate increasingly stringent regulations. The aviation sector [1, 2] is responsible for a high share of greenhouse gas emissions that must be rapidly and efficiently reduced by 2050. For this reason, research has focused on applications that could fulfill these requirements as soon as possible. Electrification has been identified as a solution for short-haul flights. However, for long-haul flights, the current battery technology is not capable of meeting the requirements in terms of overall aircraft weight, flight velocity, and range [3]. Therefore, combustion is still a principal mode of propulsion for long-haul flights. The current state of the art of combustion technologies and fuels is not

*Corresponding author

Email addresses: minierol@ethz.ch (Luigi Miniero), noirayn@ethz.ch (Nicolas Noiray)

sufficient to achieve the emissions goals. Therefore, significant research endeavors are necessary to study novel fuels and combustion regimes for aero-engines to achieve a paradigm shift in greenhouse and particulate emissions. Sustainable aviation fuels present an essential opportunity to rapidly reduce the carbon footprint of flights. Furthermore, sustainable liquid fuels are also beneficial for emission reduction without imposing substantial aircraft design modifications and infrastructure adaptation required for the employment of hydrogen [4]. Consequently, such possibilities have attracted much attention towards a better understanding of liquid fuel combustion regimes that can reduce carbon footprint and pollutant emissions while ensuring a stable flame. Among these, one of the most promising is the MILD combustion regime [5] which is based on the high temperature of reactants and a relatively low-temperature increase due to the combustion process [6], normally achieved by rapid and efficient mixing of the reactants with hot combustion products [7]. The configuration of a transverse jet in a crossflow is a well-established method to achieve favorable conditions for MILD combustion [8], which can be exploited for pollutant reduction and better flame stability. This configuration has a long standing in research studies that spans over many years due to its applicability in various fields of technology and engineering systems [9]. The vortical structures associated with the jets in crossflow are reported to provide better mixing with, and entrainment of the surrounding flow as compared to regular free jets [9, 10]. The reactive gaseous jet in crossflow has been studied extensively for different fuels over the last few years both in premixed [11, 12, 13] and non-premixed [14, 15] configurations. However, the application of this configuration to the aviation sector requires an in-depth understanding of the behaviour of liquid fuels in vitiated conditions. Although several research studies have focused on sprays in vitiated co-flows [16] and counter jets [17], the crossflow configuration has been mostly investigated for a cold [18] or a preheated air crossflow [19]. Therefore, many open research questions regarding sprays in vitiated crossflows still remain unanswered. In addition, the multi-phase physics of spray combustion and the flame stabilization mechanisms are relatively complex and call for research to fill the knowledge gap and facilitate the understanding and employment of MILD combustion in aero-engines.

The present experimental study aims at addressing some of these research questions by analyzing the combustion characteristics of a transverse spray of Jet-A1 in a vitiated crossflow. The details of the test-rig and the experimental diagnostics are described in the first part of the paper. The experimental observations and results for different liquid fuel powers and Air-to-Liquid Ratio (ALR) are subsequently reported and explained. The final remarks and future outline of the work conclude the paper.

2. Experimental setup and diagnostics

The experiments are conducted in a generic combustor with a square cross section of 62×62 mm² operated at atmospheric pressure. The first stage is composed of a 4×4 array of lean turbulent CH₄-H₂-air premixed flames. The equivalence ratio and thermal power are held constant at $\phi_{cf} =$

0.7 and 50 kW with a 5% H_2 fuel enrichment by mass. The second stage is composed of a Jet-A1 spray injected through an air-assisted atomiser, located downstream of the first stage flame. The current paper aims to describe the flame morphology and heat release as a function of the massflow air-to-liquid ratio (ALR) and thermal power of the spray which are obtained by means of OH^* -Chemiluminescence and OH - and fuel-Planar Laser Induced Fluorescence (PLIF) as illustrated in Figure 1.

Figure 1: Experimental set-up for (a) High-speed OH^* Chemiluminescence imaging, and (b) OH -Planar Induced Fluorescence. The injection point is hindered for both the configurations by a 5mm optical obstacle, as reported in a). A_{spray} and A_{airbl} correspond to the cross-sectional area of the atomiser for the liquid fuel and the airblast air.

The side view OH^* chemiluminescence images of the spray flame are taken by a LaVision StarX Highspeed camera coupled with an high-speed intense relay optics (HS-IRO, LaVision; IV Generation) as shown in Figure 1(a). The camera is focalized with a Cerco 100 mm f2.8 UV lens and a Chroma, T_l 70% at 310 nm, FWHM 10 nm bandpass interference filter. The chemiluminescence images are acquired at 5 kHz up to 1000 images (0.2s of overall acquisition time) with a photodetector size 1024×1024 and a spatial resolution of 0.08 mm/pixel. The IRO gain and gate are kept constant for all the operating conditions. During the image processing, the 1000 images are averaged and the background case without JA1 spray is then subtracted to remove the OH^* remnants coming from the first stage flame.

Next, the OH density is measured with a second setup (Figure 1(b)). The OH -PLIF measurements are pivotal to in-depth analysis of the spray flame. The LIF signal is generated with a frequency doubled dye laser (Quantel TDL 90 pumped with YG981, 20 mJ per pulse, 0.08 cm⁻¹ FWHM) tuned to the Q1(8) transition of the $OH(A-X)$ ($\nu' = 1$, $\nu'' = 0$) band near 283.55 nm. A collimated sheet from the laser beam is formed through a combination of cylindrical lenses. The laser sheet is parallel to the x-z plane and located at the centre of the atomiser orifice (see Figure 1(b)). The OH -fluorescence emissions on the laser sheet are captured with a ICCD camera (PCO

Dicam Pro), pointing parallel to the y axis (depicted in Figure 1(b)) and focalized with the same lens and filter as the one of the chemiluminescence setup. The camera frame rate is fixed at 10 Hz (spatial resolution of 0.15 mm/pixel) to acquire up to 200 images for a total of 10 s of acquisition time. The laser sheet traversed along the y-direction (below and above the spray orifice, $y=0$) in order to examine the spatial variation of reaction zones throughout the spray flame.

The OH PLIF imaging is carried out for both ON and OFF resonance frequencies. The width of the collimated laser sheet is 44 mm. In order to measure the laser excitation profile, a percentage of the incoming collimated light sheet is directed with a beam splitter on a cuvette filled with rhodamine dye solution. The ON-resonance case corresponds to the resonance frequency of the OH LIF signal which is calibrated with a Bunsen flame, whereas, the shifted frequency where OH LIF intensity is not observed is termed as OFF-resonance case. This OFF resonance case is characterised by JA1 fluorescence as well as flame chemiluminescence intensities. Note that the fluorescence from the fuel droplet/vapour clusters are associated with its aromatic content which is more broadband as compared to the OH LIF signals [20]. The mean intensity evaluated from the OFF-resonance case is deducted from the ON-resonance case to provide the corrected OH LIF intensity field. Further, both of these cases are also scaled with a background case without laser beam in order to remove chemiluminescence of the vitiated crossflow and the camera background noise. In the remainder of the paper, the mean OH-PLIF and the pixel maximum JA1-PLIF intensity among the 200 images are reported. The acquired PLIF images are normalised by the excitation beam profile.

The spray operating conditions are tabulated in Table 1.

OC #	Power [kW]	ALR [-]	J [-]	ϕ_{flow} [-]
1	2.5	2	17.75	0.123
2	2.5	4	70.89	0.122
3	7.5	2	142.48	0.341
4	7.5	4	569.05	0.325

Table 1: Summary of the operating conditions

where jet-to-crossflow momentum ratio J is defined as [18]:

$$J = \frac{(\rho_{\text{JA1}} V_{\text{JA1}}^2 A_{\text{JA1}} + \rho_{\text{airbl}} V_{\text{airbl}}^2 A_{\text{airbl}}) / A_{\text{spray}}}{\rho_{\text{cf}} V_{\text{cf}}^2} \quad (1)$$

ρ and V are the density and velocity, while the subscripts JA1, airbl and cf represent the Jet A-1, airblast, and crossflow, respectively. The areas of the liquid, airblast and spray orifice (which corresponds to the sum of the first two) are sketched in Figure 1. The crossflow density is determined from the adiabatic flame temperature of a Cantera [21] equilibrium of the first stage flame. ϕ_{flow} corresponds to the overall equivalence ratio of the flow, calculated as a Cantera equilibrium of the first and second stage gases.

It is important to underline that the variation of the atomisation air does not affect substantially the overall equivalence ratio of the flow ϕ_{flow} , which remains lean throughout all the operating conditions.

3. Observations and Discussions

OH* chemiluminescence is commonly considered a heat release marker for laminar and lean premixed flames [22]. However, it has been proven to be inadequate to provide heat release information in case of turbulent non premixed flames, where turbulent intensity and fluctuations of the equivalence ratio affect the chemiluminescence intensity signal [23, 24]. The non-premixed spray flame in a turbulent vitiated environment analysed in the present study is a highly three-dimensional and non-premixed phenomenon. For this reason, the OH* chemiluminescence images are used to represent and describe the global flame shape [25].

Figure 2 portrays variations in flame features by means of OH* chemiluminescence for spray powers of 2.5 kW ((a)-b)) and 7.5 kW ((c)-(d)) at ALR 2 and 4. The dynamics of the spray can be deconstructed into two parts: (i) the extent of spray atomisation, and (ii) entrainment variation of the crossflow, which are inextricably linked in the current work as the mass flow rate of the cross-flow remains constant for all the testing conditions.

The combination of these two effects is used to explain the global flame topology and the local changes in the flame with variation of ALR and power.

At constant ALR (Figure 2 a)-c) and b)-d)), the increase in power is associated with a momentum ratio increase (see Table 1). This condition induces a higher penetration of the jet in the crossflow, which stretches vertically the flame for both the ALR cases, without changing its location with respect to the injection point. This is highlighted by the top 75% OH* intensity region (black isocontour of Figure 2).

In contrast, at constant power and varying ALR, the higher penetration induced by the atomisation air massflow increase is combined with the localised variation of the flame shape near the spray entry. The OH* signature in this region shows a peculiar behaviour of lifting from the windward side with increase in ALR at constant power. For low ALR, the intense zone is located predominantly on the windward side, while it lifts and relocates in the leeward side with increase in ALR.

It is difficult to comment on the exact nature of reaction zones and their evolution, especially with the line-of-sight integration of the OH* intensities. In order to study the spray flame dynamics, OH-PLIF measurements are carried out at different planes of the jet. Figure 3 and 4 report the average OH-PLIF signal and the maximum at every pixel of the 200 images for the JA1-PLIF of the 2.5 kW case (3) and of the 7.5 kW (4) for ALR 2 (a)-c)) and 4 (b)-d)). An axial variation in the y direction of the crossflow temperature and composition induces an asymmetry in the jet. In particular, the positive y portion of the jet is subject to higher temperatures, which can be observed by the higher OH intensity and the smaller fuel fluorescence.

Figure 2: Average OH* chemiluminescence signal of power 2.5 kW and ALR 2(a)), 4 (b)) and power 7.5 ALR 2 (c)) and 4 (d)). The black isocontour highlights the top 75% of the intensity of each figure. All the images are normalised with the maximum intensity among all the operating conditions.

For spray power of 2.5 kW and ALR 2, the OH-PLIF images at the central plane ($y=0$) of the injection reveal predominantly high heat release zones in the windward side as presented in Figure 3 a). As the laser sheet is traversed to either side of the spray, this pattern remains largely unaltered. This particular case of low ALR and low J , suggests poor spray atomisation along with comparatively lesser entrainment of the crossflow. The OFF-resonance images for this case further reinforce the aforementioned point of the existence of individually burning bigger droplet/vapor clusters as shown in Figure 3 c). It has been well established that entrainment magnitude increases with an increase in the momentum ratio [9, 10]. The reduced crossflow entrainment is evident from the low intensities on the leeward side of the spray flame.

In contrast, the flame structure is substantially different at ALR 4 (b) of Figure 3). The lift of the flame observed in the chemiluminescence images of Figure 2 occurs due to a relocation of the high heat release zone to the leeward side of the jet. The three y positions obtained by traversing the laser in the y direction show a similar pattern. In this operating condition, the droplets are smaller compared to the lower ALR and tend to follow the air crossflow due to their lower Stokes number. This effect, combined with the higher entrainment of the crossflow induced by the higher

Figure 3: OH (a-b)) and JA1 (c-d)) PLIF at different traversing positions of the laser sheet with respect to the atomiser position. The OH PLIF shows the average of the 200 recorded images, while the JA1 shows the maximum pixel intensity among the image set. The power is kept constant at 2.5 kW, while the ALR is varied from 2 to 4.

J, ensures better mixing between the two streams. This is confirmed from the JA1 PLIF, as no fuel clusters are observed far from the injection point, especially in the reaction region identified by the high OH intensity. The high level of mixing between the evaporated fuel and the high-temperature oxidisers of the crossflow set the ideal conditions for the formation of a MILD combustion regime.

The spray flame at 7.5 kW and ALR 2 (Figure 4 a)-c)), exhibits disparate characteristics as compared to the flame characteristics of the lower power (2.5kW) case. Two reaction regions are detected, one on the windward and the other on the leeward side, which locally merge at $y=5$ plane. These two separate reaction zones can be associated with dissimilar behavior of larger and smaller droplets. On the windward side, the spatial superposition of individual fuel clusters with the reaction zone indicates the single droplet combustion regime. The fraction of the droplets with a large diameter (hence, higher Stokes number) has the tendency not to follow the air jet and penetrate in the crossflow, where they burn individually. Contrarily, JA1 fluorescence is not detected on the leeward region, which implies a rapid consumption of fuel vapor. In this condition,

Figure 4: Same conditions as Figure 3 for a kerosene thermal power of 7.5 kW.

the higher momentum ratio ensures better entrainment of the crossflow and mixing with the smaller diameter droplets convected by the atomization air. Therefore, the optimal conditions for MILD combustion are formed in this area.

At ALR 4, the 7.5 kW power spray flame Figure 4 (b-c)) has similar characteristics as the lower power one, although emphasized by the higher value of J and smaller droplets induced by the higher mass flows. The MILD reaction region (b)) is uniform, lifted, and concentrated in the leeward side of the jet for all the analyzed y positions. The combustion in the MILD regime is again confirmed by the absence of spatial superposition between fuel clusters (primarily close to the injection point) and the high heat release zone.

4. Conclusions

In the presented study, the combustion regime of a JA-1 spray injected perpendicular in a vitiated crossflow is investigated experimentally by means of high-speed OH* chemiluminescence and OH-PLIF imaging. The spray power is varied between 2.5 kW and 7.5 kW for and the ALR

between 2 and 4.

OH* chemiluminescence images provide a global overview on the location of the reaction region with respect to the injection point and of the jet penetration with ALR and power variations. However, the line-of-sight integrated field obtained with this technique does not allow for the study of the combustion regime variation which are strongly linked to the topological variations.

In order to overcome this issue, OH-PLIF and JA1-PLIF imaging are performed at different y positions. They are able to provide deeper insights into the spatial locations of the reaction zones and its relative location with fuel clusters. The formation of two different combustion regimes is identified by varying the ALR of the atomiser. This can be construed as the causality between spray atomization and extent of mixing induced by the crossflow entrainment. For low ALR, the fuel spray generates bigger droplets which do not follow their surrounding flow and tend to combust individually in the crossflow, whereas at higher ALRs fine atomization ensures smaller droplets which tend to follow the cross-flow due to their inherently low Stokes-number. This effect is combined with an increase of entrainment of the crossflow induced by the higher momentum ratio of the jet. Consequently, the droplets evaporate and mix with the oxidisers in the crossflow homogeneously, burning in MILD conditions in the leeward side of the jet farther away from the injection point. The case with the highest power and lowest ALR exhibits hybrid characteristics as the relative larger dimensions of the droplets compared to the higher ALR case are counterbalanced by a relatively high momentum ratio. This induces the formation of two distinct reaction regions, one on the windward side formed by the larger individual burning droplets and one on the leeward side induced by the mixing between the entrained crossflow and the smaller droplets.

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