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EXPERIMENTAL CHARACTERIZATION OF A PLASMA ASSISTED LIFTED FLAME

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ABSTRACT

A typical issue in aero-engine design is the flame stability, whose relevance has increased in consequence of the growing demand of pollutant emissions reduction without significant losses of the combustion efficiency. To this purpose, the use of lean and low temperature flames allows to the reduction of the potential of thermal NOx formation. However, lean flames are affected a very unstable behaviour, which increases as increasingly leaner conditions are approached up to the occurrence of the flame quenching. Flame quenching is usually anticipated by the lifting of the flame, and it occurs with the establishment of the lean blow-off (LBO) condition. In this regard, with respect to premixed-flame-based combustion, diffusive flames are of great interest due to their better stability under wide ranges of operating conditions and safety. The most typical flame control systems are passive and based on the modification of the air injection geometry such as swirlers and flame holders. Instead, in the class of the active flow control systems, plasma actuators represent a suitable choice for the flame control, due to their high flexibility and extremely short response time. Furthermore, they can be easily integrated into the burner in combination with passive control devices. Plasma actuators usually induce local heating as well as ionization of the flow in the region in proximity of the actuator. As a result, the combustion can be enhanced thanks to a better mixing between the co-flows and the modification of the reaction speed. In the field of plasma assisted combustion (PAC), non-thermal plasmas (NTPs), sometimes called non-equilibrium or 'cold 'plasmas, represent a promising solution due to the low ionization/excitation energy with respect to the total energy consumption, and the small temperature rise, which lead to a high energy efficiency. Furthermore, in the class of NTPs, the dielectric barrier discharge (DBD), also called silent discharge, represents a suitable solution thanks to the low ionization/excitation energy with respect to the total energy consumption, and the small temperature rise, which lead to a high energy efficiency. They produce non-equilibrium plasmas between two electrodes on the dielectric surface when an alternating current (AC) HV passes through them.

In this context, the strong coupling between electrical plasma discharges and combustion is still not well understood. The present work provides an experimental investigation of the stabilizing effect of a sinusoidal plasma actuation on a lean non-premixed methane/air flame in a Bunsen-type burner with annular fuel jet at ambient conditions. The flame structure has been characterized by enhancing the lift-off condition up to the flame blow-out. The efficiency of the plasma actuation has been evaluated for different actuation condition and a comparative analysis has been performed aiming to characterize the dynamic behavior of the lifting flame with and withour plasma actuation, and investigate the plasma actuation capability in flame stabilization and reattachment

Keywords: Plasma assisted combustion, non-premixed flame, plasma actuation, DBD

1 INTRODUCTION

A typical issue in aero-engine design is the reduction of NOx emissions without relevant losses of the combustion efficiency, and low temperature flames of lean fuel mixture represent a promising solution [1,2]. However, lean flames are affected by strong instabilities that can easily bring to flame quenching as leaner conditions are approached, i.e. the flame blow-off. The incipience of the blow-off condition is usually anticipated by the lifting of the flame, whose behavior has not been deeply understood yet. With respect to premixed or partially premixed flames, which could use pilot flames flame stabilization [3], non-premixed diffusive flames manifest a better stability under wide ranges of operating conditions and safety [1] [4].
In literature, several techniques have been investigated to avoid the flame instability. The stabilization of turbulent non-premixed flames has been studied in [5]. In lifted diffusion jet, the flame stability is influenced by local flame extinction in the flame area where the outer mixing layer merges with the central flame front [6]. Instead, the stabilization of the edge flame for non-premixed flames propagating in laminar and turbulent flows was also affected by the velocity gradient and the burnt gas expansion on edge flame propagation [7] propagation. Fokaides et al. [8] experimentally characterized the flow pattern, the mixing evolution and the temperature distribution of a lifted-stabilized swirl flame near its lean blowout.
Concerning the control of the flame stability, nowadays passive control systems are of common use in the field of aeroengine combustor design. They are based on the modification of the air injection geometry (such as swirlers) and flame holders, which promote the flame stability by means of the establishment of large-scale vortexes. These flow structures permit a turbulent mixing and hot gases recirculation and extend the mixture flammability range. In addition to passive control systems, active flow control devices can also be adopted, which allow adjustment of control parameters according to real-time operation conditions. Among them, a very promising technique is based on the use of plasma, due to their high flexibility and extremely short response time.
Previous studies have demonstrated the positive effect of plasma actuation on combustion, as they can stabilize ultra-lean flames, decrease of ignition delay time and extend flammability limits [8]. Plasma discharges can affect the combustion in terms of thermal, kinetic and transport mechanisms [9, 10]. In fact, combustion can be improved by the local production of new radicals and ionized species as well as by momentum and turbulence promotion by the motion of the electric carriers due to the electric field. Recent studies investigated the flame stabilization by using non-thermal plasma (NTPs) electrical discharges, sometimes called non-equilibrium or ‘cold ’plasmas., thanks to the high energy efficiency related to a lower ionization/excitation energy with respect to the total energy consumption, and the consequent decrease in temperature. Also, characteristic electron temperatures in plasma discharges are of few electron volts, which permit to dissociate the fuel and to produce free radicals [11, 12]. High voltage (HV) discharges have been also investigated with the aim to improve the fuel/air mixtures ignition [13, 14], to increase flame propagation [15, 16], to enhance flame stabilization [17, 18, 19, 20, 21], and to extend flammability limits [22].
On of the most promising non-thermal plasma device is the dielectric barrier discharge (DBD). Non-equilibrium DBD plasmas can be produced between two electrodes on the dielectric surface when an alternating current (AC) HV passes through them [23, 24, 25, 26, 27]. In the present work, the effect of a sinusoidal plasma actuation on the lift-off height, as well as the flame length and shape, has been experimentally investigated in a Bunsen-type burner with an inner CH4 jet surrounded by an outer air jet. Several experimental campaigns have been carried out, in order to characterize the dynamic behavior of the lifting flame with and without plasma actuation, and investigate the plasma actuation capability in flame stabilization and reattachment.

2 EXPERIMENTAL SETUP, METHODS AND METHODOLOGIES

The experimental setup is composed of a coaxial Bunsen burner equipped with a plasma actuator and two gas feeders for air and methane. Along each feeding line, a flow meter read the flow rate. The electrical setup consisted in a high voltage (HV) generator, a HV probe and a current transformer, which allowed for the measurement of the the electrical power (Figure 1).

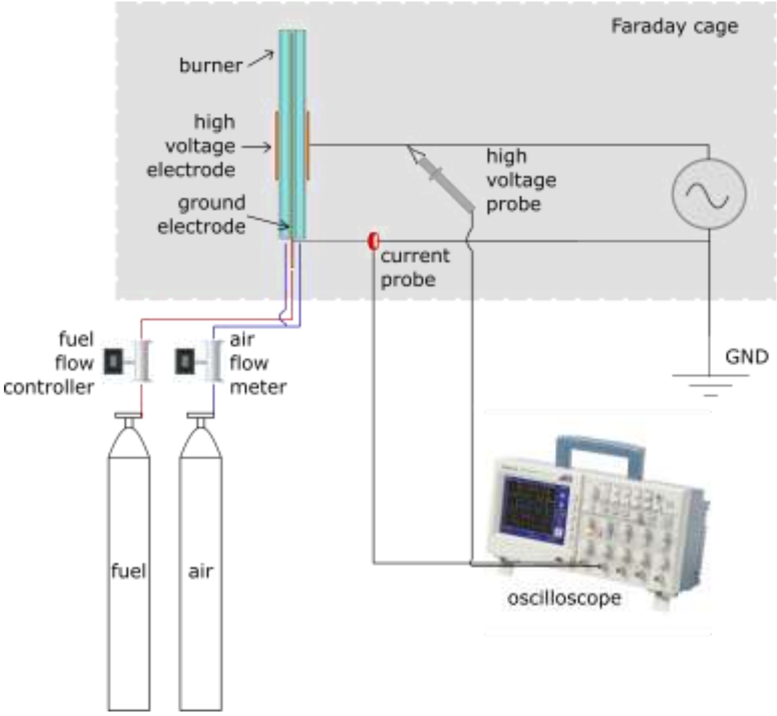

Figure 1: Experimental setup: (a) general schematic; (b) Sketch of the burner geometry together with the plasma actuator and reference system.

In particular, the Bunsen burner was composed of two coaxial quartz tubes. The inner one had an external diameter of 10 mm, its thickness was 1 mm. The coaxial outer tube had an external diameter of about 30 mm, a thickness of 2 mm. The coaxial flow configuration was a typical normal diffusive flame (NDF), namely the inner and the outer tubes were fed by methane (CH_4) and air, respectively. The top ends of the two coaxial tubes were aligned as shown in Figure 2, thus there was no mixing zone inside the quartz tube and the flame ignition took place at the exit of the quartz tubes. Concerning the accuracy of the flow rate measurement, it was ±3% of reading ± 0.3% full-scale for the air flow, and ±0.8% of reading ±0.2% full-scale for the methane flow.

A DBD reactor coupled with a suitable power supply defined the non-thermal plasma generation syste. The DBD reactor consisted of an internal copper needle having a diameter of 1 mm which was connected to the ground (herein referred as grounded electrode). It coupled with a copper corona of 30 mm length, 1 mm thickness and 30 mm inner diameter. The corona was fastened to the outer surface of the outer quartz tube by screws, and connected to the high voltage (herein referred as HV electrode). A sinusoidal high frequency/HV signal was provided to the HV electrode by means of a HV generator (the PVM500 Plasma Resonant and Dielectric Barrier Corona Driver, commercialized by Information Unlimited®) powered the HV electrode, while the other electrode was connected to ground. As shown in Figure 2, the standoff distance S_{SO}, i.e. the distance between the upper lip of the plasma grounded electrode and the mixing region, was set to -40 mm.

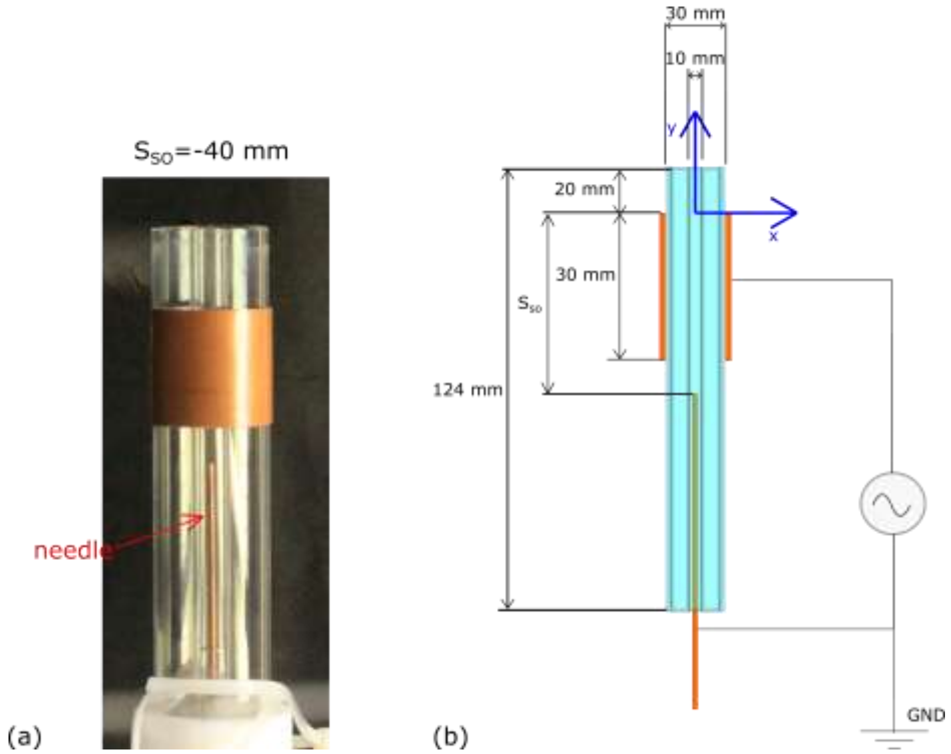

Figure 2: Plasma actuator DBD configuration: (a) picture; (b) geometry and dimensions.

The applied voltage $V(t)$ signal was acquired by using the HV probe Tektronix P6015A, with a measurement accuracy of ±3% of reading. Instead, the current flowing in the circuit $I(t)$ was measured through a current transformer Bergoz mod. CT-C1.0-BNC with accuracy of ±0.5%. Both the HV probe and the current transformer were connected to the oscilloscope (Tektronix TDS2024C) and the respective signals were recorded simultaneously with an accuracy of $\pm$ 3% of reading. The acquisition sample rate was set to 25 MHz and each measurement point was given by the average of 128 samples. Measured data were used for determining the electrical power dissipation. Different peak-to-peak voltages V_{pp} voltages were tested at fixed actuation frequency equal to 20 kHz.

Based on voltage and current measurements, the electrical power consumption of the DBD was computed as follows:

$$P_{el} = \frac{1}{T}\int_0^T I(t) \cdot V(t) \cdot dt; \qquad (1)$$

where T is the period of the applied voltage.

In order to characterize the impact of the plasma actuation, a high-speed camera (Memrecam GX-1F), equipped with Sigma Macro lens 105mm, captured the flame dynamicse. In particular, 500 single-images (resolution of 348 pixels x 480 pixels) have been acquired for each test condition, at a sampling rate of 500 Hz.

3 TEST CASES

Different experimental campaigns were performed, as highlighted by the final test matrix of the experiments in Table 1. All experiments have been conducted by fixing the air flow rate and increasing fuel flow rate. More precicely, the air mass flow rate was fixed to about 1.54 g/s during runs 1 and 2. The lifting condition characterized the flame behavior during tests both with and without plasma actuation, thus runs 3 to 5 were performed by increasing the applied

voltage V_{pp}, and lowering the air flow rate to 1.35 g/s so that the flame reattachment was experienced in presence of plasma actuation.
The fuel flow rate was varied during each experimental campaign. The fuel-to-air equivalence ratio Φ was defined as $\Phi = (\dot{m}_f/\dot{m}_a)/(\dot{m}_f/\dot{m}_a)_{st}$, where $\dot{m}$ is the mass flow rate and the subscripts f, a and st denote the fuel, the air and the stoichiometric conditions respectively. A value of 17.19 was assumed for $(\dot{m}_a/\dot{m}_f)_{st}$. For the combustion power Q_b calculation, the CH_4 lower heating value was chosen equal to 50 MJ/kg.

Table 1: Test matrix of experiments and operating conditions. Plasma actuation frequency of 20 kHz.

	Test case	S_{SO} [mm]	$\dot{m}_a$ [g/s]	$\dot{m}_f$ [g/s]	Φ [-]	V_{pp} [kV]	P_{el} [W]	Q_b [W]
Run 1	1a	-40	1.54±0.03	0.0005±0.0001	0.006±0.001	0	0	27±5
	1b			0.0011±0.0001	0.012±0.001			55±5
	1c			0.0016±0.0001	0.018±0.001			82±5
	1d			0.0027±0.0001	0.031±0.001			137 ±5
	1e			0.0055±0.0002	0.061±0.003			270±10
Run 2	2a	-40	1.54±0.03	0.0005±0.0001	0.006±0.001	10.7±0.3	0.071±0.002	27±5
	2b			0.0011±0.0001	0.012±0.001			55±5
	2c			0.0016±0.0001	0.018±0.001			82±5
	2d			0.0027±0.0001	0.031±0.001			137 ±5
	2e			0.0055±0.0002	0.061±0.003			270±10
Run 3	3a	-40	1.35±0.03	0.0011±0.0001	0.014±0.001	0	0	55±5
	3b			0.0033±0.0001	0.042±0.002			164 ±5
	3c			0.0055±0.0002	0.070±0.003			270±10
Run 4	4a	-40	1.35±0.03	0.0011±0.0001	0.014±0.001	10.5±0.3	0.073±0.003	55±5
	4b			0.0033±0.0001	0.042±0.002			164 ±5
	4c			0.0055±0.0002	0.070±0.003			270±10
Run 5	5a	-40	1.35±0.03	0.0011±0.0001	0.014±0.001	16.2±0.4	0.26±0.01	55±5
	5b			0.0033±0.0001	0.042±0.002			164 ±5
	5c			0.0055±0.0002	0.070±0.003			270±10

4 FLAME IMAGING RESULTS

Previous investigations highlighted that the standoff S_{SO} =-40 mm has higher performance, therefore it was chosen for the present investigation.
At an air flow rate equal to 1.54±0.03 g/s (runs 1 and 2), even though the plasma discharge was not able to promote the flame reattachment, it significantly impacted on the flame dynamics. The plot in Figure 3 shows the modification of the average value and the standard deviation of flame lift-off height signal retrieved by means of image processing. In general, the plasma actuation becomes less effective on lowering lift-off height with increased fuel flow rate. However, an inversion condition was pointed out at fuel flow rate between 0.0016 and 0.0027 g/s, corresponding to fuel jet velocity approximately ranging between 0.05 m/s and 0.08 m/s. The application of plasma discharges to decrease the lift-off height is effective until the fuel jet velocity reaches 0.05 m/s. Beyond this value, the plasma has no significant impact on the flame lift-off height, as confirmed by the flame imaging shown in Figure 4. In fact, in comparison with the clean configuration involving cases of the experimental run 1, the presence of the plasma actuation extended the flame region toward the burner exit section for fuel jet velocities lower than 0.05 m/s (test cases 2a, 2b and 2c). However, at higher fuel jet velocity (test case 2d and 2e), this effect weakened even though the amplitude of the lift-off height oscillations reduced with respect to the clean case, and the lifting flame behavior became more stable. The dynamic inversion condition is figured out in Figure 5, which compares the lift-off height signals in absence (blue curve denoted by “clean”) and in presence (red curve denoted by “act”) of plasma actuation, before the inversion (Figure 5 (a)) and after the inversion.

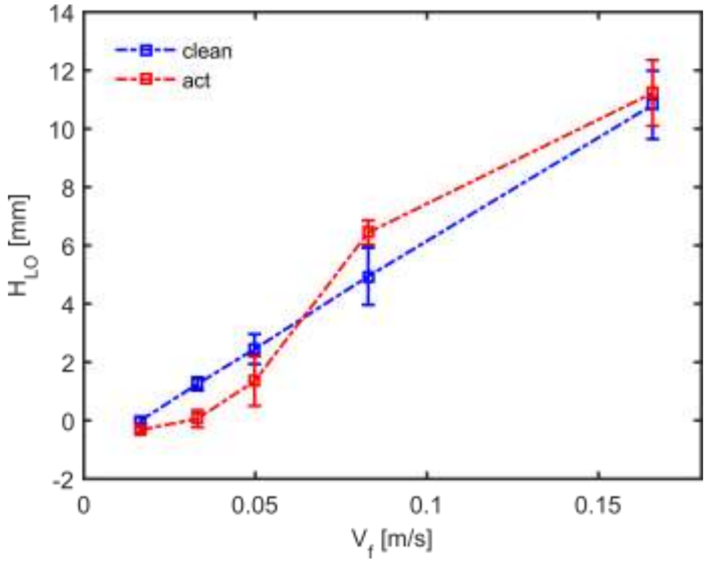

Figure 3: The effect of the jet fuel velocity on the flame lift-off height for flames with and without the discharge at a fixed air flow rate equal to 1.54 g/s.

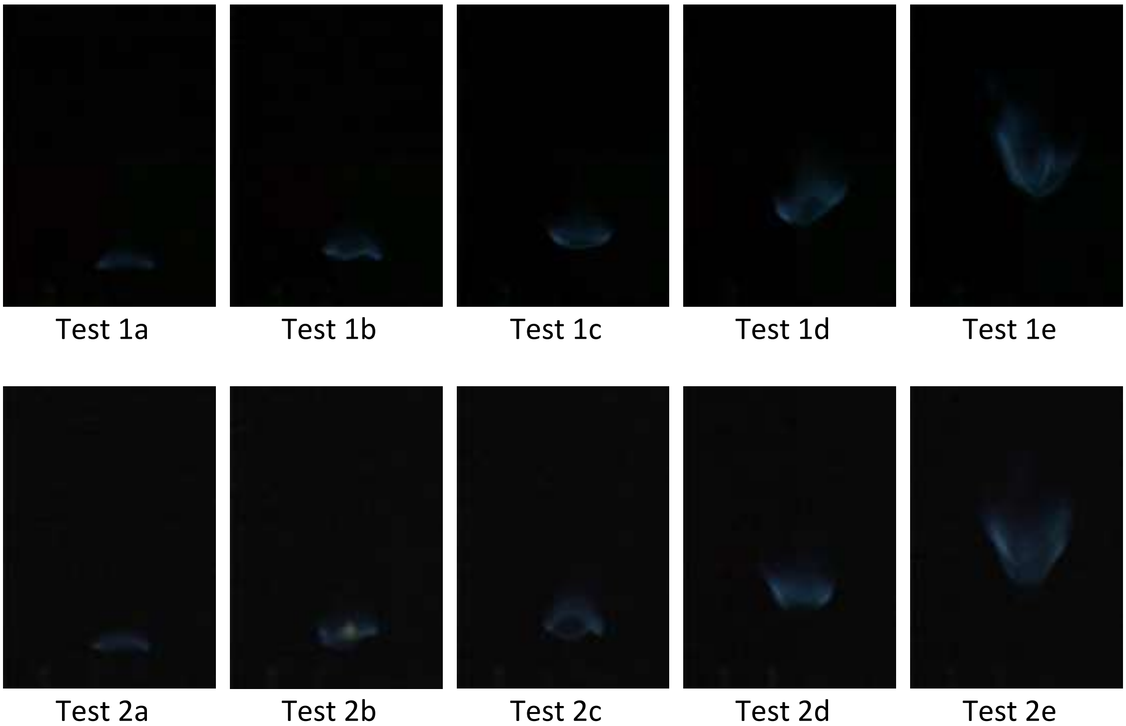

Figure 4: Representative instantaneous images of flame without plasma discharges and plasma-attached flames, at different fuel flow rates and fixed air flow rate at 1.54 g/s.

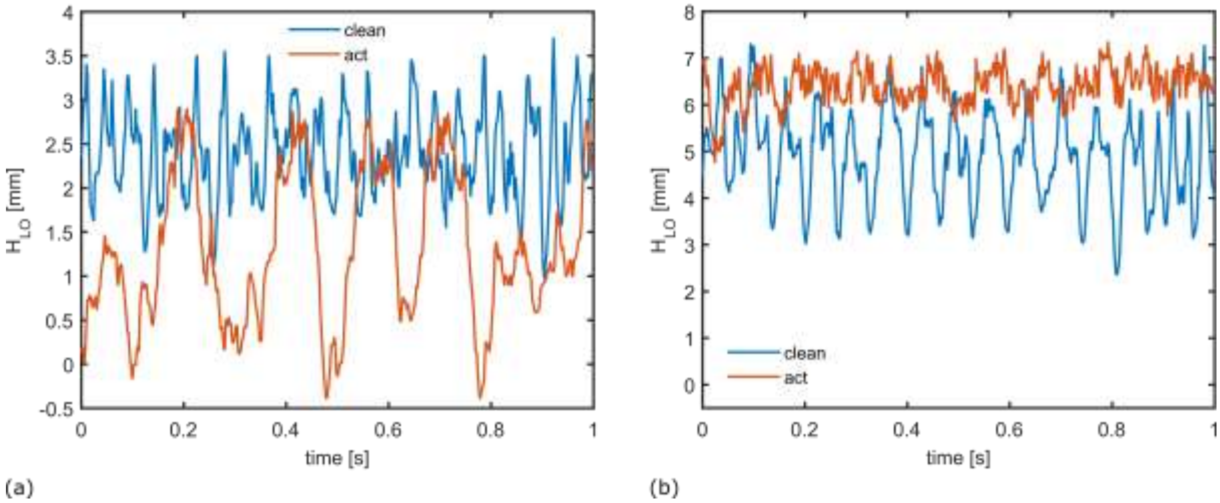

Figure 5: Comparison between lift off height signals with and without plasma actuation: (a) test 1c (clean) vs test 2c (act); (b) test 1d (clean) vs test 2d (act).

Instead, the Fast Fourier Transform (FFT) of these signals highlights the impact of the plasma actuation on the frequency content of the flame, as shown in Figure 6. In particular, the main frequency reduced from about 21.5 Hz to the range [4 – 8] Hz before the dynamic inversion, while the oscillation amplitude almost doubled (Figure 6 (a)). After the dynamic inversion, the plasma significantly reduced the frequency content as well as the energy content of the lift-off height oscillations, as evinced in Figure 6 (b).

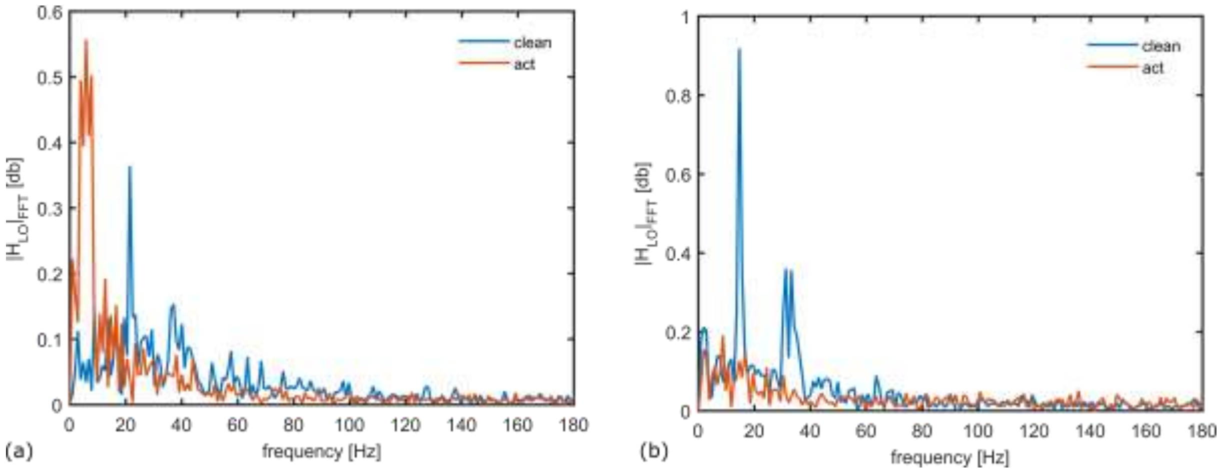

Figure 6: Comparison between the FFT signals of the lift off height, with and without plasma actuation: (a) test 1c (clean) vs test 2c (act); (b) test 1d (clean) vs test 2d (act).

By decreasing the air flow rate, the beneficial effect of the plasma actuation enhanced. In fact, when fixing the air flow rate to 1.35 g/s while keeping constant the fuel flow rate, the presence of plasma was capable to reattach the flame, which anchored at the nozzle exit. This is confirmed in Figure 7, which shows raw images of flames with and without plasma for each test case of runs 3, 4 and 5. Consequently, the flame moved from the lift-off condition (test cases 3a, 3b and 3c), to a partial reattachment condition at V_{pp}=10.5 V (test cases 4a, 4b and 4c), before to full reattach at V_{pp}=16.2 V (test cases 5a, 5b and 5c). Furthermore, as applied voltage and the dissipated power increased, the flame grew up and exhibited a higher intensity, so that to appear more stable, symmetric and strongly anchored to the nozzle exit. Instead, at fixed applied voltage, the fuel flow rate is seen to have a different impact on the flame of the plasma actuated cases with respect to the clean cases. In absence of plasma actuation, the flame was lifted, and the increase of the fuel flow rate corresponded to a higher lift-off height of the flame up to the blow-off condition. Conversely, when the plasma actuation was enabled, the flame reattached, and the height of plasma assisted flame increased proportionally to the fuel flow rate.

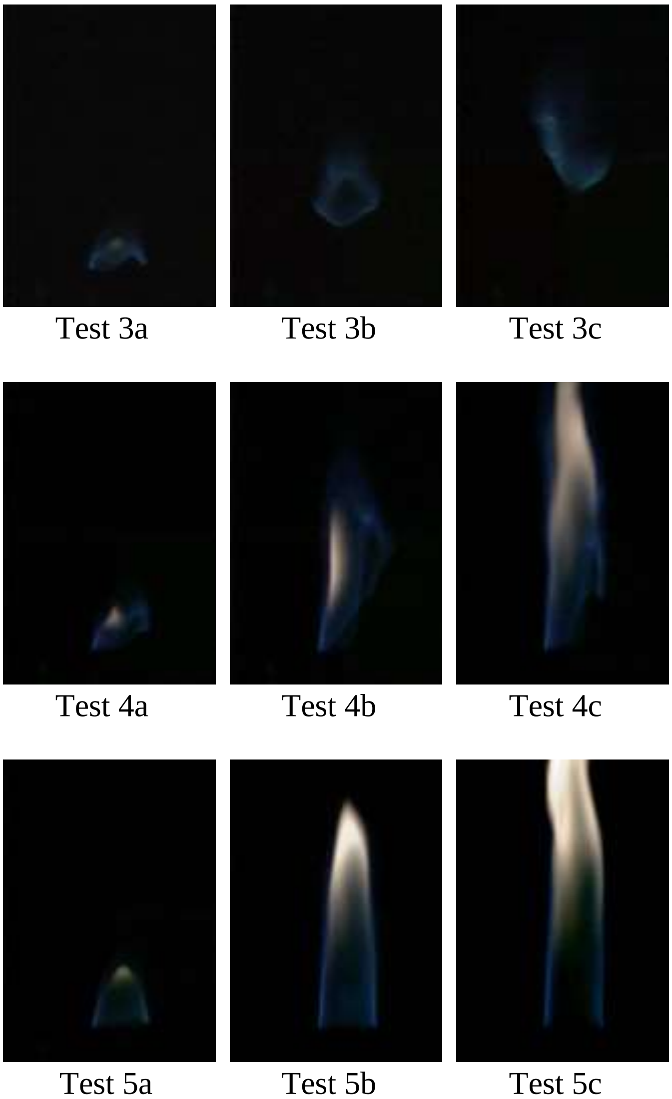

Figure 7: Representative instantaneous images of flame without plasma discharges and plasma-attached flames, at different fuel flow rates and fixed air flow rate at 1.35 g/s.

5 CONCLUDING REMARKS

The present work provides a preliminary experimental investigation concerning the impact of sinusoidal DBD plasma discharges on the dynamic behavior of lifted non-premixed jet flames fueled with methane. In particular, a sinusoidal plasma actuation was applied to a Bunsen-type burner with an inner CH4 jet surrounded by an outer air jet. The effects of the plasma actuation on the imaging-derived lift-off height signals were analysed, in combination with a qualitative evaluation of the modification of the flame length and shape. Different experimental campaigns have been carried out at several air and fuel flow rates, as well as by varying the plasma power conditions. In general, it was observed that the presence of plasma has an impact on decreasing the lift-off height and altering the flame behavior. The application of plasma discharges to flame stabilization leads to plasma-attached flames or plasma-enhanced lifted flames, depending on the air and fuel flow rates. In particular, at air flow rate of 1.54 g/s, the application of plasma discharges allowed to decrease the lift-off height until the fuel jet velocity was below about 0.05 m/s thanks to the extension of the flame region upstream toward the burner exit section. Instead, beyond the dynamic inversion condition, the plasma exhibited no significant impact on the average lift-off height, even though both the frequency and the energy contents of lift-off height oscillations reduced and the lifting flame behavior became more stable, as confirmed by the FFT analysis of the lift-off height signals. The effect of the plasma actuation improved by reducing the air flow rate. At air flow rate of about 1.35 g/s, plasma-assisted flame reattachment was evident at each fuel velocity, in combination with an increasing flame height proportionally to the fuel jet velocity.

6 ACKNOWLEDGEMENTS AND REFERENCES

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