IMPROVEMENT OF LEAN FLAME STABILITY OF INVERSE METHANE/AIR DIFFUSION FLAME BY USING COAXIAL DIELECTRIC PLASMA DISCHARGE ACTUATORS

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Abstract

Low environmental impact is a main issue in the design of novel combustion systems, as aircraft engines. In this context, the present work investigates the possibility to increase the combustion efficiency of a lean flame through the use of sinusoidally driven dielectric barrier discharge (DBD) plasma actuator. The effect of the plasma discharge on a lean non premixed methane/air flame in a Bunsen-type burner has been studied for two different configurations: the normal diffusive flame (NDF) and the inverse diffusive flame (IDF). The flame behavior was investigated by chemiluminescence imaging through an intensified CCD camera. Optical filters were installed in front of the camera, aiming to selectively record signal from the chemiluminescent species OH, CH, or CO2*. This allowed evaluating the changes occurring in presence of plasma actuation in term of flame emissions. It was shown that the plasma effects are significantly influenced by the burner and DBD configuration. A plasma power of approximately 25 W permitted to increase the air mass flow rate at which lean blowout appears; it rose up to 30 % for low methane flow rate and up to 10% at high fuel flow rate.

Keywords

Diffusive methane/air flames; inverse flames; blowout; plasma actuator

Highlights

- A coaxial-cylinder dielectric barrier discharge is used on a CH_4/air Bunsen flame
- DBD has a significant influence on the flame shape of both IDF and NDF flame
- At low $(O/F)_{mom}$ DBD leads to the backward propagation of IDF flame
- Chemiluminescence imaging underlines a rise of CO_2* with DBD
- DBD leads to an evident improvement of the lean blowout limits

1. INTRODUCTION

Diffusion-flame-based combustion systems are of great interest in power plants and aeronautical jet engines, due to their better stability under wide ranges of operating conditions and safety with respect to premixed-flame-based combustion [1–3]. Premixed or partially premixed flames can easily blow off in absence of external stabilization facilities [4], hence pilot flames are frequently used to stabilize a turbulent premixed/partially premixed flame jet. In contrast, a normal diffusive flame (NDF) that can be established in a coaxial burner with a central fuel jet and an annular oxidizer jet has a small tendency to blow off, even if it presents low heat release rate and high soot emission, and might present incomplete combustion [5,6].

The inverse diffusion flame (IDF), a special kind of the non premixed flame, is observed to produce less soot than the normal diffusion flame. Hence there has been a growing interest in the inverse non premixed coflow flames [7].

The turbulent inverse jet flames are used in various fields as rocket engines and staged combustion systems. The injection of central oxidizer with annular hydrogen or methane jet in rocket engine combustors helps in minimizing the oxidation of combustor walls [8–12].

The flame structure of inverse diffusion flame is different from the premixed flame and the normal coaxial jet flame. Previous works [13] investigated the effect of air–fuel velocity ratio on the characteristics of IDF. It was shown that the high momentum between the central air jet and fuel jet ensured better entrainment of flow momentum fuel along with the ambient air and it enhanced mixing in the IDF configuration, in comparison with normal diffusion flame. Furthermore, methane–oxygen IDF leads to enhanced radiation heat flux with respect to NDF given by central fuel and annular oxygen jets [14].

However inverse CH_4/air coflow flames present reduced stability limits with respect to normal non premixed CH_4/air coflow flames [7,15].

Recently investigations have been performed regarding the flame stabilization by the use of non-thermal plasma (NTPs) electrical discharges, sometimes called non-equilibrium or ‘cold’ plasmas.

Non-thermal plasmas present high energy efficiency, due to low ionization/excitation energy with respect to the total energy consumption, and small temperature rise. Characteristic electron temperatures in these discharges are of few electron volts, which permit to dissociate the fuel and to produce free radicals [16,17].

Several studies focused on the application of high voltage (HV) pulses to improve the ignition of fuel/air mixtures [18,19], to increase flame propagation [20], to enhance flame stabilization [21–23], and to extend flammability limits [24].

In [25] and [26] it was shown that nanosecond HV pulses might reduce the ignition delay time. However, few works were focused on the application of the plasma discharges for the flame stabilization [25] and [26]. A plasma actuator is substantially a device able to change locally the chemical and fluid dynamic state using the action of an applied electric field [27].

In [28] Nanosecond Repetitively Pulsed (NRP) discharges produced by electrical pulses of about 10 kV during 10 ns at a frequency of 30 kHz were applied to stabilize a lean premixed methane/air flame at atmospheric pressure. The plasma created in the recirculation zone improved the flame stabilization and reduced the lean extinction limit by about 10-15% with respect of the baseline case with plasma off, with an electrical power consumption less than 1% of the power of the flame.

In [29] a repetitive discharge at 9 kHz and with voltage pulse duration of about 100 μs was used to extend the flammability limit of a lean premixed propane/air mixture at atmospheric pressure.

A promising non thermal plasma source is the DBD. Non-equilibrium DBD plasmas can be produced between two electrodes on the dielectric surface when an alternating current (AC) HV passes through them [27,30,31].

The DBD, also called silent discharge, can be simply operated and it has relatively low cost in producing non-equilibrium plasma, high discharge stability and simple operability of equipment.

Repetitive pulsed plasmas have been applied to stabilize normal methane jet flames [32] and propane jet flames [33]. In [33] it was shown that the liftoff height of propane and air-diluted propane jet flames is reduced by more than 50% in the presence of a DBD.

Previous studies investigated the plasma actuation mostly in premixed burners or normal coaxial burner with central fuel jet even if in several fields inverse configurations with central oxidizer and annular fuel jet are of great attention.

Even if there is a need for stabilizing the methane flame in conditions near the blowout due to the varied applications of this configuration ranging from rocket combustor to gas burners [34], there is a lack in the literature regarding the stability of inverse methane diffusion flames by DBD plasma devices.

Hence in the present work the flame behavior and the blowout limits of lean methane inverse diffusive flames were experimentally investigated in presence of a DBD. A sinusoidal pulsed plasma produced by electric pulses with electrical dissipated power up to 33 W has been used to stabilize and improve the combustion efficiency of bunsen-type normal and inverse diffusive flames. Different operating parameters have been considered, in terms of: air and methane flow rates, voltage amplitude of the sinusoidal signal applied to the plasma actuator and its geometrical configuration.

Flame imaging was done by using an intensified CCD camera, equipped with various optical filters to selectively record signal from the chemiluminescent species OH*, CH*, or CO_2*. This allowed evaluating the changes occurring in presence of plasma actuation in terms of flame emissions.

2. EXPERIMENTAL SET-UP AND METHODOLOGIES

2. 1 Experimental apparatus

The experimental set-up consists of: (1) a coaxial burner equipped with the plasma actuator and associated gas feeders (air and methane); (2) an HV generator and (3) a measurement system, involving: a personal computer (PC), a compact Charge-Coupled Device (CCD) camera, an intensified CCD camera, a HV probe, a current probe and an oscilloscope.

2. 2 Burner configurations and gas supply system

The gas feeder is composed by air and methane tanks, connected to the burner through pressure regulators and flow controllers. The flow rates of air and methane are controlled by two flow meters: the SFAB-50U-HQ12-2SV-M12 of Festo® for the air, with a measurement accuracy of ± 3 % of measured value, and the EW-32907-57 of ColeParmer ® for the methane, with a measurement accuracy of ±0.8% of reading.

The burner is composed of an internal stainless steel tube (external diameter 8 mm and internal diameter 7 mm) and by a coaxial quartz tube (10 mm of internal diameter, 1 mm of thickness). The mixing region, which is the zone between the top ends of the two coaxial tubes, is 60 mm long. It is the zone in which the reactants mix themselves and its dimension influences the mixture formation and the zone where the flame clings to.

Two different fueling configurations have been used: in the first one the fuel flows in the outer coaxial quartz tube and air in the inner tube, this leads to the plasma activation of methane (herein referred as “IDF configuration”). The second configuration has an inner fuel jet surrounded by an outer air jet (herein referred as “NDF configuration”). The gases are ignited at the end of the quartz tube.

The positioning of the powered electrode with respect to the superior edge of the steel tube influences the plasma action. The standoff distance, s, which is the distance between the plasma region and the mixing region, was set alternatively to 0 and to 6 mm. In the first case (s=0) the influence of the plasma actuation affects the fuel-air mixing, in the second case (s=6mm), the distance is sufficient to ensure that only fuel was activated, without significant effects on the mixture.

2. 3 DBD reactor and electrical system

The non-thermal plasma generation system involved a DBD reactor and a power supply. The steel tube was connected to the ground (herein referred as “grounded electrode”). A copper tube (80 mm long, thickness 0.6 mm), placed on the outer surface of the quartz tube was instead connected to the HV (herein referred as “HV electrode”).

The HV generator was the PVM500 Plasma Resonant and Dielectric Barrier Corona Driver, commercialized by Information Unlimited® [35]. A sinusoidal waveform actuation signal with different voltage amplitudes and a frequency of 20 kHz was applied to the copper tube.

A high voltage probe (*Tektronix P6015A*), a current probe (*Bergoz Current Transformer CT-D1.0-B*) and an oscilloscope (*Tektronix TDS2024C*) were used to retrieve the voltage-current characteristic curves as a function of time t and the electrical power dissipation $\overline{P}_{el}$.

The HV probe was located on the HV connector side and the current probe on the ground side. The HV and current probes were connected to the oscilloscope, and the measured signals (applied voltage and current flowing in the discharge, respectively) were recorded with an accuracy of ±3%. In a single acquisition the oscilloscope captured 2500 points at a sampling rate of 25 MHz, therefore two time periods (*T*) for each signal. A number of 128 acquisitions were recorded and averaged. The obtained signals of averaged voltage $\overline{V}(t)$ and of averaged current $\overline{I}(t)$ were used for calculating the $\overline{P}_{el}$ value.

A schematic of the electrical setup is reported in Figure 1(a) and the respective picture is in Figure 1(b).

It is pertinent to note that a Faraday cage was used to shield the cameras from any electromagnetic interference due to the high electric fields required to generate the plasma discharge.

2.4 Imaging tools

The visible flame appearance was captured using a Canon Power Shot SX240 HS digital camera with ISO 800, a focal length of 18 mm, an aperture of f/8.0, and an exposure time of 1/8 s.

The chemiluminescence emissions were also acquired using the Phantom Miro M320S® High-Speed Digital Camera CCD by La Vision® [36], with a maximum frame rate at full resolution (1920 x 1080) of 1540 Hz, a sensitivity of 1100 ISO, interframe time of 1.4 µs and a pixel depth of 12 bit. The camera was equipped with an intensifier by Lambert Instrumentation® [36]; the intensifier has photocathode material S20 (UV), Phosphor screen P46 and a spectral range for max response of 270-450 nm. The intensifier gain was set to 600 for all the chemiluminescence acquisitions. The quantum efficiency (QE) of the Intensifier/CCD coupling for the two wavelength is about 0.6% for OH*, 4.80% for the CH* and 1.9% for the CO_2*. The images for the analysis were taken with a resolution of 200 pixels x 400 pixels, a flame view area of 70x140 mm. For each test point a set of 50 single-images was recorded. The recording rate was 10 frames per second with an integration time of 50000 µs and 2×2 pixel hardware binning.

2. 5 Test conditions

Experiments were conducted at different air and fuel mass flowrates, which means different values of the air-to-fuel momentum flux ratio $(O/F)_{mom}$ that is defined as:

$$\left(\frac{O}{F}\right)_{mom} = \frac{(\rho u^2)_{air}}{(\rho u^2)_{fuel}} \tag{1}$$

Where ρ is the density and u is the exit velocity.

For the chemiluminescence acquisitions the data are reported in Table 1. The $(O/F)_{mom}$ assumed values of 34 and157 for the IDF and 540 for the NDF. For the IDF, the equivalent methane/air flow ratio φ was changed in the range 0.73–1.58; the Reynolds number, Re, based on the hydraulic diameter of the burner exit and the bulk gas velocity is in the range 479.75-1531.12 for the air and 42.21-63.31 for methane.

The NDF was investigated at an equivalent methane/air flow ratio φ equal to 0.73, $(O/F)_{mom}$ equal to 540.55, Re_{air} equal to 656.19 and Re_{CH4} equal to 147.72. All the experiments were conducted keeping the pressure at atmospheric level and the inlet temperature, for both fuel and air, was 288 K.

3. Results and discussion

3.1 Electrical characterization of the plasma

The $\overline{P}_{el}$ was calculated by:

$$\overline{P}_{el} = \frac{1}{2T}\int_0^{2T} \overline{I}(t)\overline{V}(t)dt \tag{2}$$

Numerical integration was performed by the trapezoidal rule and the corresponding uncertainty, estimated by standard uncertainty analysis methodology [37], resulted in ±4.2%.

All measurements were made with the flame present. An example of an acquisition (i.e. averaged signals of the applied voltage and of the current flowing in the discharge) is reported in Figure 2, for both the IDF and NDF configurations and for the two different standoff distances.

The typical plasma discharge current curve encompasses two main components: (1) a sinusoidal one due to the capacitive effect between both electrodes, which did not correspond to any discharge phenomenon, and (2) a series of pulses, characteristic of dielectric barrier discharges in filamentary regime and due to the settling of simultaneous microdischarges between the exposed electrode and the dielectric [27]. The high frequency oscillations that we see in the averaged current curve, comes from the averaging of the plasma microdischarges.

Different values of the voltage amplitude were tested; for each actuator excitation condition and for each burner operating condition the power consumption has been estimated and reported in Figure 3 and Table 2.

Figure 3 reports the power dissipation in function of the applied peak-to-peak voltage. It is evident that the rise of the applied voltage leads to an almost linear increase of the dissipated power. Moreover, it is possible to notice that, at the same methane and air flow rates ($\dot{V}_{air}$=7.5 l/min, $\dot{V}_{CH4}$ =0.6 l/min) and similar applied voltage, the electrical power dissipation in the IDF configuration is higher than in the NDF. Moreover, the change in the standoff distance doesn't influence significantly the dissipated power for the NDF configuration, while a more significant change is noticeable for the IDF configuration.

In general, the electrical power consumption was between 5 W and 35 W. These electrical power dissipation values are similar to the ones investigated in literature works on non-thermal plasma in coflow jet diffusion flames using a dielectric barrier discharge [38,39,40,41].

3.2 Comparisons between normal jet diffusion flame and inverse jet diffusion flame

3.2.1 Visible flame morphology and structure

The influence of the plasma effects on the flame shape and luminosity for the different flame configurations can be qualitatively observed from direct flame visualization.

Figure 4 and Figure 5 show the effect of progressively higher-power of the plasma on the flame for both flame configurations, at the same methane and air mass flowrates (equivalence fuel/air ratio equal to 0.73), and at the two different standoff distance values for the plasma device. At these conditions, combustion power from the oxidation of the fuel is about ~275.62 W using the lower heating value of methane. Furthermore the $(O/F)_{mom}$ is equal to 157.49 for the IDF and 540.55 for the NDF.

When the actuator is on, the electrode area is occupied by a uniform, blue-violet plasma, with a rise in intensity when the plasma power increases. Results show that the response of the flame to DBD discharges significantly depends on the average power deposited by the discharge. For IDF flames, the combustion occurs entirely outside the quartz tube, while for NDF flames, after ignition the flame propagates upwards only and the reactions mainly take place inside the quartz tube in the mixing region. For both the standoff distance values in presence of plasma actuation the NDF flame length considerably increases with the plasma power, upward the quartz tube, and a rise in the intensity is evident at the flame tip. At high plasma power the flame is bluish at the base and yellowish in the conical tip.

The plasma actuation leads to a more significant increase of the IDF flame intensity with an increase of the yellow/orange region that might partly correspond to the soot emission. The enhanced anchoring of the flame on the edge of the quartz tube is also evident. At standoff distance of 6 mm the yellowish zone is smaller with respect to the case at same plasma power and s=0, moreover this effect is visible only at the highest power level.

3.2.2 CCD imaging chemiluminescence

The detection of chemiluminescence emission associated to specific excited radicals can yield relevant information on the combustion process.

Even if chemiluminescence emission images are not quantitative, the images for the cases with and without the plasma discharge are acquired with the same camera settings for each radical, such that relative differences between the tested cases can be underlined.

In methane-air flames, there are three chemiluminescence emitters in the UV-VIS: hydroxyl OH*, methylidyne radical CH* and CO_2* radical. It should be underlined that the CH* intensity as measured by the ICCD camera also includes the chemiluminescence contribution of CO_2*, hence CO_2* emissions have been also measured.

Averaged OH*, CH* and CO_2* chemiluminescence images, based on the acquisition of 50 instantaneous images, are shown in figures 6-8 as a function of increasing plasma power for both IDF (top) and NDF flames (bottom) at the same equivalent fuel/air ratio, $\varphi = 0.73$.

In the present section the region of data extraction in the chemiluminescence image is mainly from the reaction zone of the flame, as shown by the red box on the visible flame image in Figure 6-8. The axial position equal to 0 corresponds to the exit of quartz tube.

As the OH* intensity is high in the flame front, the measured two-dimensional imaging of OH*qualitatively indicates the instantaneous shape of the reaction zone.

Comparing the two different burner configurations, it can be noticed that more OH* and CH* are generated in the IDF flame.

Both the OH* and CH* distributions for the NDF configuration are quite uniform and confined inside the quartz tube, as shown in figure 6 and figure 7.

Regarding the IDF flame (Test 6), in the baseline case without actuation the OH* emissions mainly occur in an annular ring around the centerline, with peaks of the chemiluminescence intensity located at about 20 mm from the quartz exit.

In presence of the plasma discharge at s=0 mm, the ring boundary becomes vague and an increase of the emission intensity is evident in proximity of the quartz exit. Furthermore, an axial movement of the area with the maximum OH* intensity upstream towards the quartz exit is present at high plasma voltages and then plasma dissipated power levels. On the contrary, the OH* area keeps almost unvaried when the applied voltage and the plasma power increases for the IDF with s=6 mm.

The enhancement of OH* production by plasma discharge at s=0, more than at s=6mm, might be due to the fact that, when the plasma discharge is applied to the mixing region of fuel and air, the methane oxidation is more efficient. Furthermore, the radicals produced by plasma have their lifetimes. If the distance between the plasma discharge area and the reaction zone is too far, as it might be in the case of standoff distance s=6mm, the active specie cannot reach the combustion area and it affects the combustion.

The flame images in figures 4-5 show an increase of the luminosity, especially for the IDF flame, increasing the plasma power. In order to verify if this is due to an increase of soot, it is interesting to investigate also the CH* chemiluminescence emissions, as shown in figure 7. For the low sooting flame the CH* chemiluminescence should be relevant in the flame emissions while, for sooting flames, the peak luminosity may be caused by soot radiation.

As CH* radical is mainly produced in the heat release zone of the flame, it can represent the inner layer of the reaction zone. CH* is a radical that highly depends on temperature, hence it is highest in rich flame conditions.

Figure 6 and figure 7 show that the OH* and CH* intensity distributions are similar. Oxygen reacting with CH* produces an OH* radical and a carbon monoxide molecule. This reaction is relevant in the reaction zone where CH* is found, and it dominates the overall formation in low pressure environments, responsible for almost 90% of the OH* signal at atmospheric pressure [36].

The CH* chemiluminescence images show that the intensity of CH* emissions slightly increases with the rise of the plasma power, applied in the mixing region (s=0). The high voltage discharge mainly leads to a change in the emission area; for the IDF the peak in CH* emissions shifts toward the tube, especially along the centerline, increasing the plasma power.

The CH* distribution exhibits a “M shape” structure, which indicates the higher propagation speed in the center of flame. Under plasma actuation, the flame propagation speed is improved, which pushes the thin reaction zone against the upward flow, giving a new balance between the flow and the burning zone.

This is also confirmed in figure 8 by the CO_2* chemiluminescence emissions, which manifest, for both the fueling configurations, a significant rise of their intensity for high plasma power; the CO_2* emission appear also more relevant than the ones of the other two radicals.

3.3 Effect of DBD plasma actuator configuration on the IDF flame

3.3.1 Visible flame morphology and structure

The air-to-fuel momentum flux ratio $(O/F)_{mom}$, governs the IDF structure [18].

Figure 9 shows the flame appearance for the different fueling and air flow rates. Two comparisons were mainly performed. The first one was done by fixing the fuel flow rate and changing the $(O/F)_{mom}$ (the first two rows of images in the figure); the second one was carried out fixing the $(O/F)_{mom}$ and the equivalent fuel/air ratio, while varying the fuel and the air flow rates (the last two rows of images in the figure).

For the case at $(O/F)_{mom}$ equal to 34.30 ($\dot{V}_{air}$=3.5 l/min, $\dot{V}_{CH_4}$=0.6 l/min), in the baseline configuration (Test 1), the flame has a hollow annular structure and a very bright ring boundary can be observed. This might be due to the methane flow velocity that is much smaller than the air velocity; hence the mixing of gases is not sufficient in the center region in which the mole fraction of methane is lower than the flammability limit. Regarding the effect of the DBD, by increasing the power of the plasma discharge (with the rise of the applied voltage) flame modifications are observed, as the augmentation of the flame length and the increase in yellow/orange luminosity, which means in the soot region. These effects are more evident at s=0 rather than s=6mm. This might justify the change of flame shape and lenght, and soot formation, which seem to be mainly due to the ionic wind effect.

Increasing the $(O/F)_{mom}$ up to 157.49 ($\dot{V}_{air}$=7.5 l/min, $\dot{V}_{CH_4}$=0.6 l/min), the momentum of the central air jet plays a major role in the IDF flame height for a fixed fuel jet velocity, leading to a decrease of the visible flame length with the increase of the air flow rate. At low $(O/F)_{mom}$, equal to 34.30 (test 1), the unburned fuel and carbon particles decomposed by fuel cannot be further oxidized due to the absence of O_2, which forms the obvious upper luminous zone (yellow). Under fuel-lean condition (test 6), the adequate supply of oxygen provides the opportunity for further oxidation, leading to the increase in OH* generation, as it will be shown in the results of the chemiluminescence OH* distributions.

Furthermore, as the amount of air added through the central jet was increased, the color of the flame significantly changed from bright yellow-orange on the flame tip (Test 1) to almost pure light blue (Test 6). Soot formation is also greatly suppressed, as the luminous zone becomes shorter and fainter, and the flame becomes principally soot-free. This can be attributed to reduction of the soot surface growth rate, and to the direct oxidation of the soot. Moreover, because of the higher air flow rate, the inner IDF becomes taller, while the visible flame height of the outer diffusion flame decreases.

When voltage supplied to the DBD actuator is increased (hence the plasma power rises) the flame maintains its shape even if the yellow luminosity increases with the plasma power for standoff distance equal to 0.

Fixing the $(O/F)_{mom}$, equal to 34.30 and lowering the fuel mass flow rate (Test 17-21), the flame has a hollow annular structure for the baseline case (Test 17). In this condition the influence of the DBD on the flame shape is more relevant with respect to the case at the same $(O/F)_{mom}$ and higher fuel flow rate.

It can be noticed that the flame structure changes drastically rising the intensity of the plasma discharge, if s= 0 mm. Furthermore, in these cases (test 18 and test 19) the flame propagates backward into the quartz tube and the hollow size becomes smaller (test 18). At the highest voltages (test 19) the ring boundary disappears. If the standoff distance is equal to 6 mm (test 20, test 21), the influence of DBD on the flame structure becomes weakened and the structure of the hollow flame keeps almost invariable when the applied voltage is increased. This confirms that the enhancement of the combustion is mainly due to the acceleration of the methane-air mixing process, due to the electric field in proximity of the mixing region (in the case s=0mm) and results in both the hollow flame elimination and the insurgence of downward propagating flame. It is remarkable that the soothing zones were altered by the electric field, being longer in height in the case of s=0 mm. Furthermore, the blue zone between the quartz end and the sooting zone along the axis was reduced with the rise of the applied voltage.

3.3.2 CCD imaging chemiluminescence

Figures 10-12 report the chemiluminescence emissions recorded for the IDF under different operating conditions. The spontaneous flame emission images still underline the enhancement of combustion with plasma discharges for all the flow conditions.

As shown in the previous section, the flame height reduces with the increase in central air jet momentum, because more fuel is likely to entrain into the central air jet; it can result in intense mixing within a shorter region to produce smaller flame rate. Furthermore, a shift of the luminous OH* and CH* zones towards the quartz exit is evident in the presence of the plasma discharge with s=0 mm; for all the flow rate conditions, this shift between the cases with and without the plasma is more significant for lower $(O/F)_{mom}$. The lean condition, at $(O/F)_{mom}$ equal to 157.49, shows an appreciable increase in the OH* emission intensity for the cases with plasma discharge compared to the baseline; this is less appreciable at $(O/F)_{mom}$, equal to 34.30.

Fixing the $(O/F)_{mom}$, equal to 34.30 and lowering the fuel mass flow rate (Test 17-21) the position of the maximum OH* and CH* emissions in the flame was apparently lowered by the plasma discharge with respect to the previous fuel flow rate condition (Test 6-15). Furthermore there is an appreciable increase in the length of the CH* zone (comparing first and third row of images in figure 11), in particular for the maximum plasma power and s=0 mm. The CH* and OH* chemiluminescence emissions are more affected by plasma discharge at low fuel flow rate, which means low hydrocarbon concentration.

Regarding the CO_2* emissions in figure 12, it can be seen that at low $(O/F)_{mom}$ (tests 1-5 and tests 17-21) the plasma enhancement is less significant with respect to the lean condition at $(O/F)_{mom}$ =157.49. It should be remarkable that at lean condition the [O] concentration is higher, leading to a greater rise of CO_2*. It is clear that the plasma significantly enhances the amount of combustion products at $(O/F)_{mom}$ =157.49, with a rise of the peak values of the CO_2* and of the area at high CO_2* concentration when increasing the plasma power.

Figure 13 shows the plots of the axial distribution of the relative OH*, CH* and CO_2* intensity that are extracted from the chemiluminescence images.

The OH* and CH* distributions present double peaks in the baseline cases (tests 1-6-17) that shift towards the burner exit in presence of the plasma discharge. The shift is more significant for the OH*, it is approximately of 5 mm at the lowest fuel flow rate (test 19) and it reaches the10 mm value at the high fuel flow rate and leanest condition (test 10) with an electrical dissipated plasma power of approximately 27 kW. The plasma discharge leads to a reduction of the initial reaction zone, where fuel and oxygen are mixed partially (depending on the action of interdiffusion) with a shift of the maximum intensity of the OH and CH emissions towards the burner surface.

Increasing the plasma power applied to the lean flame (baseline flame corresponds to test 6) it is evident an appreciable increase in the magnitude of OH* intensity.

Furthermore, for all the flow conditions, increasing the plasma power there is an appreciable increase in the width of the CO_2* zone.

3.4 Effect of plasma on blowout limit extension

The enhancement of the stable flame operation region, by delaying lean blowout to lower equivalent fuel air ratio, is one of the main aims in the use of the plasma discharge. Hence, the influence of the plasma excitation to extend the lean blowout limits of the inverse methane/air flame was investigated by holding the fuel mass flow rates and varying the air flow rate in discrete steps towards the lean flame blowout limits. The blowout air flow rate is an indicator of flame stability, and a high blowout air flow rate shows that combustion continues to occur under lean-burn conditions.

The air flow rates, in correspondence of which blowout occurred, were recorded for different values of methane flow rate. Furthermore, two levels of voltage amplitude (hence of plasma power levels) were applied.

By increasing Re_{air} for given Re_{CH4} the flame experiences a transition from the stable regime into the unstable near-blowout regime and finally blowout. Figure 14 shows the LBO limit that has been defined as percentage rise of the maximum air flow rate to blowout, for methane flow rates between 0.26 and 0.76 lpm. When the plasma actuator is on, it leads to an evident improvement of the LBO limit, with a large increase for low fuel flow rate (low equivalence ratio). The best performance in terms of improvement of LBO limit is for the configuration at s=0 mm. In the DBD configuration with s=0 and the highest voltage, which corresponds to the plasma power in the range 23-29 W, the LBO (air flow rate at blowout) could be extended by approximately 30 % relative to the baseline lean blowout limit (actuator off) at the lowest fuel flow rate. At highest methane flow rate the maximum increment of the LBO limit is of about 10%.

At low fuel flow rate the rise in plasma power increases significantly the LBO limit, while at high methane flow rate there is no convenience in the increase of the plasma power, due to the same LBO limits reached with both the plasma actuation voltages. These effects may be caused by a “ionic wind” between the applied electric field and the “chemi-ionized” species in the flame reaction zone. Furthermore, for each test, the power of the plasma discharge was held constant, thus the discharge energy density deposited into the fuel (defined as the discharge power divided the fuel flow rate) decreased as the methane flow rate increased. Thus, the magnitude of the discharge energy density seems to affect the flame blowout limit.

Furthermore, if the discharge acts on the fuel (s=6mm) the LBO limit deteriorates at low fuel flow rate even if the same amount of energy is coupled to the flame. This could confirm that DBD plasma causes radical production/enhancement and it influences the mixing, while the heating effect could be less significant.

Figure 15 shows the blowout limits on a Re_{air}-$(O/F)_{mom}$ and Re_{CH4}-$(O/F)_{mom}$ diagrams since $(O/F)_{mom}$ is expected to be one of the major parameters for non-premixed flame stability in some applications, e.g., bipropellants [7].

It is quite evident that the $(O/F)_{mom}$ is not influenced by the DBD at high methane Reynolds number, while reducing it the plasma enhancement of the $(O/F)_{mom}$ is obtained with high plasma power levels and s=0.

The diagrams confirm the potential of DBD plasma discharges to improve the combustion performance of the inverse CH_4-air flames and the data represent a suitable database for modeling the lean IDF flame near the blowout limit in presence of DBD plasma discharge. Flame blowout enhancement with plasma was experimentally obtained with a low level of plasma power, less than 29 W.

4 Conclusions

A coaxial-cylinder DBD plasma actuator is used to activate a diffusive methane/air Bunsen flame. Two different fueling configurations have been used, the normal diffusive flame and the inverse diffusive flame.

Results show that the impact of plasma on the flame is strongly dependent on the DBD configuration, in particular on the standoff distance and the flow conditions, as the fuel/air ratio and the air-to-fuel momentum flux ratio $(O/F)_{mom}$.

Imaging in the visible spectral range shows that, in absence of actuation, the combustion occurs entirely outside the quartz tube for IDF, while the reaction in NDF (at the same fuel/air equivalent ratio of the IDF) mainly occurs inside the quartz tube in the mixing region because after ignition the flame propagates upward only. In presence of DBD actuation, increasing the applied voltage and thus the plasma power, the NDF flame length increases upward the quartz tube. At the highest plasma power that has been tested, approximately 34 W, the flame is bluish at the base and yellowish in the conical tip.

The plasma actuation leads to a more significant rise of the IDF flame intensity with an increase of the yellow/orange region that might partly correspond to the soot emission.

At low $(O/F)_{mom}$, equal to 34.30, the flame has a hollow annular structure and a very bright ring boundary can be observed in absence of actuation. If the DBD is on, the flame propagates backward into the quartz tube and the hollow size becomes smaller.

Increasing the $(O/F)_{mom}$ up to 157.49 a decrease of the visible flame length is evident, and the color of the flame changes significantly from bright yellow-orange on the flame tip to almost pure light blue. When the DBD is on, the flame maintains its shape even if the yellow luminosity increases with the plasma power.

Qualitative chemiluminescence imaging indicates that, during plasma discharge, the shape of the reaction zone of the flame changes especially for the IDF flame, which is shifted upstream towards the burner surface; this indicates a direct effect of the electric discharge on flame chemistry. Comparing the two different burner configurations more OH* and CH* are generated in the inverse flame at the same fuel/air ratio.

Chemiluminescence imaging also underlines a rise of the peak values of the CO_2^* and of the area at high CO_2^* concentration, increasing the plasma power.

Finally, it was found that the DBD leads to an evident improvement of the LBO limit up to 30 % relative to the baseline lean blowout limit (actuator off), at the lowest fuel flow rate and for the configuration at standoff distance equal to 0 mm. At the highest methane flow rate the maximum increment of the LBO limit is of about 10%.

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Table 1
Settings for the different test conditions.

	$\dot{V}_{CH_4}$ (l/min)	$\dot{V}_{air}$ (l/min)	u_{CH_4} (m/s)	u_{air} (m/s)	Re_{air}	Re_{CH_4}	$(O/F)_{mom}$
CH_4 activated IDF	0.6	3.5	0.35	1.52	714.52	63.31	34.30
	0.6	7.5	0.35	3.25	1531.12	63.31	157.49
	0.4	2.35	0.24	1.02	479.75	42.21	34.79
Air activated NDF	0.6	7.5	0.22	4.42	656.19	147.72	540.55

Table 2
Dissipated electrical power in different test conditions.

Test case	Methane flow rate [l/min]	Air flow Rate [l/min]	Standoff [mm]	Power Dissipation [W]
		IDF		
1	0.6	3.5	-	0
2			0	21.5±0.9
3				27±2
4			6	19±0.8
5				24±1
6	0.6	7.5	-	0
7			0	7.6±0.3
8				13.5±0.6
9				22±0.9
10				27±2
11				35±2
12			6	6.6±0.3
13				12.6±0.5
14				19.8±0.8
15				26±2
16				33±2
17	0.4	2.35	-	0
18			0	21.2±0.9
19				27±2
20			6	20.1±0.9
21				26±2
		NDF		
22	0.6	7.5	-	0
23			0	6.7±0.3
24				13.3±0.6
25				20.8±0.9
26				27±2
27				34±2
28			6	5.2±0.2
29				12.3±0.5
30				19.8±0.8
31				26±2
32				33±2