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Plasma Assisted Flame Stabilizationin a Non-Premixed Lean Burner

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Abstract

In recent years, the application of plasma actuators in different engineering fields was considered particularly interesting. It was successfully applied for the cold flow control in aero engines and turbo-devices. One important application concerns the use of non-equilibrium plasma for plasma-assisted ignition and combustion control.
The reduction of nitric oxides (NOx) in aircraft engines, gas turbines, or internal combustion engines has become a major issue in the development of combustion systems. A way to reduce the NOx emissions is to burn under homogenous lean conditions. However, in these regimes the flame becomes unstable and it leads to incomplete combustion or even extinction. Thus, the major issue becomes to stabilize the flame under lean conditions. In this context the present work aims to demonstrate the possibility to increase the combustion efficiency of a lean flame through the use of nanosecond repetitively pulsed plasma (NRPP). A NRPP produced by electric pulses with amplitude up to 40 kV, pulse rise time lower than 4 ns and repetition rate up to 3.5 kHz has been used to stabilize and improve the efficiency of a lean non premixed methane/air flame in a non-premixed Bunsen-type burner.
The burner is optically accessible permitting the imaging acquisitions of the flame region. The flame behavior was acquired using a high rate CCD camera in order to capture the differences between the baseline conditions and the actuated cases. Moreover a post-processing technique showing the jagging of the flame in different conditions was applied to evaluate the changes occurring in presence of plasma actuation in term of flame area weighted respect to the luminosity intensity. It was shown that the plasma significantly allows stabilizing the flame under lean conditions where it would not exist without plasma.

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Keywords: microburner; plasma; combustion; imaging; Heywood Circularity Factor

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1. Introduction

The reduction of pollutant emissionshas become a major issue in the development of combustion engines systems. Nitric oxides (NOx) emissions are strongly related to the flame temperature[1], which is influenced by the fuel equivalence ratio. The temperature could be reduced by burning the fuel in lean conditions[2]. However, in these conditions, the flame shows instabilities and eventually extinction events[3, 4]. Thus, the stabilization of the lean flame is of great importance. In previous works many attempts have been made to improve combustion efficiency at lean conditions using an electric field that can positively affect flame stability, flame propagation speed, and combustion chemistry[5]. High-voltage pulses have been applied to the ignition of fuel/air mixtures[6]. The application of nanosecond high-voltage pulses through a plasma actuator mightmight permit to reduce the ignition delay time, as reported in [7] and [8].

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 [9] but it may be done in different manner. Few works investigated the plasma assisted flame stabilization ([10], [11]).Inthese works a coaxial combustor was chosen for the experiments and different plasma actuator configurations were tested (respectively DBD and glow type actuation). In Pilla et al.[12]a nanosecond pulsed plasma produced by repetitive electrical pulses at an amplitude of 10 kV, a duration of 10 ns and a frequency of up to 30 kHz was used to stabilize and improve the efficiency of a 25 kW lean, turbulent, premixed propane–air flame operated at atmospheric pressure.Stabilization was reached with a low level of plasma power, approximately equal to 0.3% of the maximum power of the flame. In [13]the flammability limit of a lean propane/air mixture at atmospheric pressure was extended by using a repetitive discharge at 9 kHz, with voltage pulse duration of order 100ms.

Previous studies investigated the plasma actuation mainly in premixed burners or coaxial burner with central fuel jet. However in several fields reverse configurations with central oxidizer jet surrounded by annular fuel jet are of great interest. Because of the varied applications of this last configuration ranging from rocket combustor to gas burners, there is a need for stabilize the flame in conditions near the blowout[14]. In the present work ananosecond repetitively pulsed plasma produced by electric pulses with amplitude up to 40 kV, pulse rise time lower than 4 ns and repetition rate up to 3.5 kHz has been used to stabilize and improve the efficiency of a lean non premixed methane/air flame in a non-premixed Bunsen-type burner in both the configurations: central fuel jet and central oxidizer jet.

Nomenclature

Φ	Equivalent Fuel/Air ratio [-]
V	Voltage Amplitude [kV]
f	Repetition Frequency [Hz]
u	Flow velocity [m/s]

2. Experimental set-up, testing conditions and post-processing techniques

The experiments were realized using a specifically designed burner equipped with a plasma actuator (see Fig. 1). The internal stainless steel tube of the burner has an external diameter of 8 mm and athickness of 0.5 mm.It is connected to the grounded node of the high voltage (HV) generator. The coaxial quartz tube has 10 mm of internal diameter and 1 mm of thickness. It is enveloped with a 3 cm long mesh electrode connected tothe HV generator.The nanosecond pulse to drive the plasma actuator was achieved by means of a nanosecond pulse generator (NPG-18/3500 ofMegaImpulse Ltd®[15]). This generator produces high voltage pulses with a maximum peak voltage of 40 kV, a pulse rise time of about 4 ns, a pulse repetition rate up to 3.5 kHz and energy up to 30mJ/pulse.

To test the capability of the nanosecond pulse to control the flame, different levels of voltage and pulse repetition rate were applied. The peak voltageis defined as a percentage of the full-scale value.

Hence both the voltage and the frequency were set to 0% (baseline case, "NO PLASMA"), 25%, 50%, 75%, 100% that corresponds to 0, 10, 20, 30, 40 kV and 0, 875, 1750, 2625, 3500 Hz.

The mixing region and the standoff distance are respectively 40 mm and 5mm long, as shown in Figure 1.Two configurations have been tested. In the first one –called central methane jet - the fuel flows in the central tubeand air in the annular tube, with plasma activation of air;in the second one– called central airjet - the oxidizer is fueled in the central orifice while the fuel in the annular tube, hence plasmaactivation regards the fuel.The flow rates of air and methane are controlled by flow meters.For the present investigation air flow was set to 5.188 l/min (u = 2.25 m/s) while the methane flow rate was set at three values: 0.725, 0.154 and 0.103 l/min (respectively u=0.43m/s, 0.09m/s and 0.06m/s). Hence the global equivalent fuel/air ratio, related to the stoichiometric ratio, ranges between 1.33 and 0.188 and it was calculated considering all the flow rates drove in the burner. All the experiments were conducted keeping the pressure at atmospheric level and the inlet temperature, for both fuel and air, at 288 K.

The visible flame appearance is 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 high speed events occurring towards blowout are captured using the high speed CCD camera MEMRECAM GX-3® of NAC Image Technology (visible spectral range emission)[16] was used with a frame rate of 200 Hz.

In order to quantify the effect of the actuation on the flame shape and intensity, the area integral of the pixel intensity in the flame area has been calculated. This parameter is related to the heat release from the flame and has been adimensionalized with respect to the value at the baseline case.

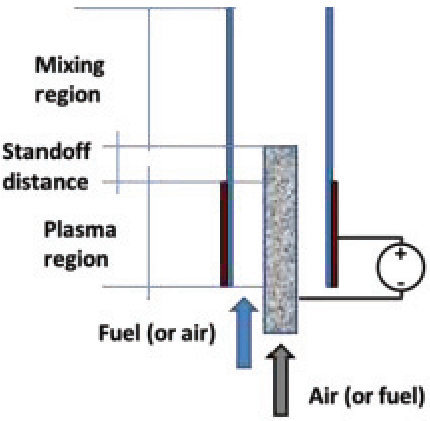


Fig. 1 Scheme of the microburner. Gases flows are controlled via two mass flow controllers. (A) quartz tube, (B) conductor mesh

Fig. 2 Example of the flame in proximity of lean blow out without (on the left) and with (on the right) the plasma actuation for two burner configurations

In order to establish the flame area a thresholding procedure, based on the Otsu's method [15], has been also implemented. It minimizes the mean square errors between the original image and the resultant binary. This resultant matrix permits to select only the meaningful pixel in the raw images and the sum of the luminosity intensity of these pixels is also representative of the heat release from the flame.

3. Experimental results and discussion

In Fig.2 there is an example of the flame image acquired in proximity of blowoutwithout and with plasma actuation. In the central oxidizer jet configuration the high momentum central air jet augments the entrainment of low momentum fuel along with the ambient air. Faster fuel–air mixing can be achieved in this jet flame configuration due to the formation of shear layer eddies at the interface of air–fuel jets. Besides this, the flame structure of jet flame is distinct from the one of central fuel jet configuration. Even if the blowout characteristics of the two burner configurations are found to be quite different, for both of them it is evident the effect of the actuation in the stabilization of the flame.

In Fig. 3it is possible to observe the results obtained applying the plasma actuation for a lean combustion conditionin the second configuration. The effect of the plasma on the flame is evident both increasing the voltage (Fig. 3a) and the repetition rateof the signal (Fig.3b). The higher the pulse voltage and the repetition rate are, the more luminous and powerful the discharge will be.

Thefrequency variation produces the most significant changein the flame shape improvingthe stability and the homogeneity of the flame. It is also evident the enhanced anchoring of the flame on the edge of the quartz tube when the effect of the plasma becomessignificant.While for low power the actuation (voltage amplitude up to10 kV or repetitionrate up to 1750 Hz) does not produce anappreciableeffect of flame control.The effect of anchoring and stabilization of the flame is clearly related to the discharge power. The effects start to be visible approximately at a voltage of 20 kV and a repetition rate of 1750 Hz.

The magnitude of the plasma effect depends also on the fuel/air ratio. This is qualitatively shown in Fig. 4 where the cases with and without plasma control are compared at two values of equivalent fuel/air ratio.The case in Fig. 4a is a fuel lean condition, while in Fig. 4b the mixture is rich. While in (a) the plasma effect is clearly observed, the same cannot be said for case (b). When the flame is stable the plasma actuation does not produce effects on the flame shape even if it leads to an increase of the flame intensity.

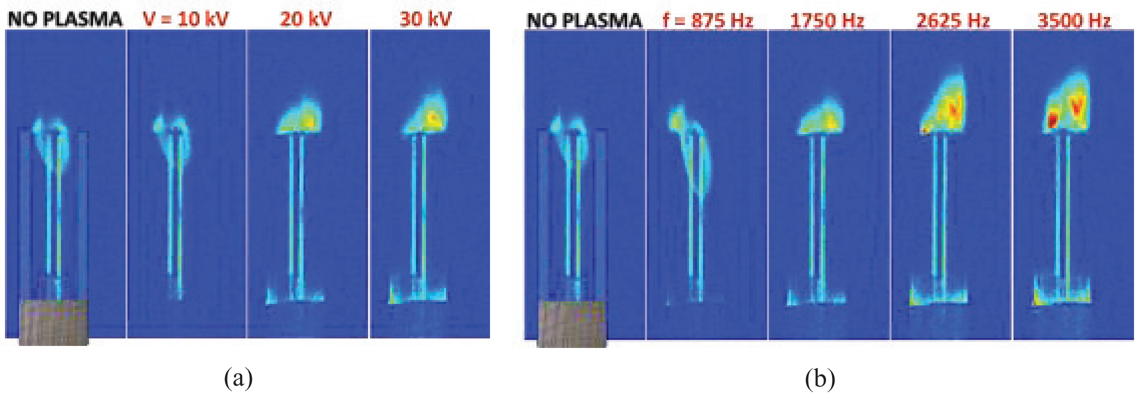
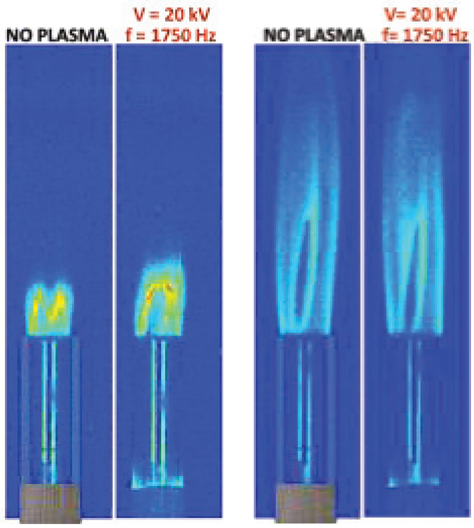
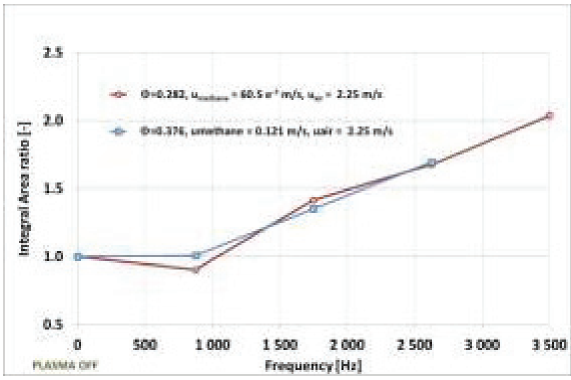


Fig. 3Effect of plasma on the flame shape: Φ=0.282, $u_{methane}$ = 0.06 m/s, u_{air}= 2.25 m/s, (a) variation of applied voltage fixing the repetition frequency to 1750 Hz(b) variation of frequency rate fixing the voltage to 20 kV.

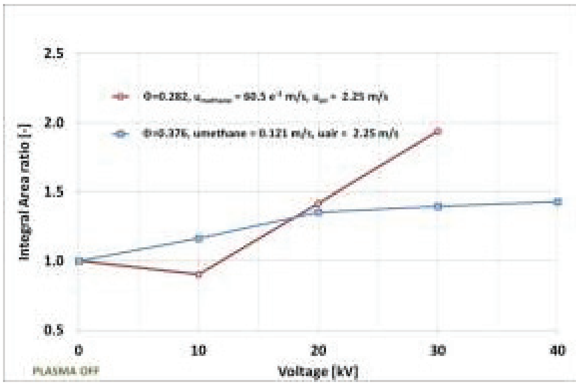


(a) (b)

Fig. 4Effect of plasma actuation on the flame shape, V = 20kV, f = 1750 Hz: (a) Φ=0.376, $u_{methane}$ = 0.121 m/s, u_{air}= 2.25 m/s, (b) Φ=1.330, $u_{methane}$ = 0.428 m/s, u_{air}= 2.25 m/s.



(a)



(b)

Fig. 5 Effect of plasma actuation on the Area Integral ratio changing the actuation conditions: (a) V=20 kV and different values of voltage amplitude (b)f=1750 Hz and different values of repetition frequency.

This is more evident looking at the integral area of the pixel intensities, as shown inFig. 5.The figureshows the trends of the Area Integral ratio, defined as the ratio between the area integral value in the actuated case and the baseline without actuation, at different voltage amplitudesand repetition frequencies. This parameter underlines the effect of the plasma on the flame luminosity. The low power actuation does not produce observableeffects, both changing the frequencyor the amplitude of the applied voltage. On the contrary the effect is more significant for high values of amplitude and repetition frequencies, when the area increases up to two times the value in the baseline case.

4. Conclusions

The present work investigates the use of a plasma actuation to enhance the flame stability of a leancombustion burner under two different configurations: central fuel jet and central oxidizer jet. Visualobservations showed that nanosecond repetitively pulsed discharge can significantly influence the flameshape. Plasma actuation effects become evident when voltage and/or frequencies reach values ofrespectively 20 kV and 1750 Hz. Above these limits the effect of the actuation is also evident in term ofluminosity of the flame and it was quantified using the area integral ratio as representative parameter.Furthermore the plasma assisted combustion is shown to be a promising way for the stabilization of a leanflame.

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Biography

M.G. De Giorgi is Assistant Professor in Aerospace Propulsion, at the University of Salento, Italy. The main research activities were carried out in the fields of Aerospace Propulsion and Energy. She is the author of more than 80 papers, published in international journals or presented at international and national congresses.