STABILIZATION OF A TURBULENT PREMIXED FLAME USING A NANOSECOND REPETITIVELY PULSED PLASMA

G. Pilla, D. Galley, D.A. Lacoste, S. Ducruix, F. Lacas, D. Veynante and C.O. Laux
Laboratoire EM2C, CNRS UPR 288 – Ecole Centrale Paris, Chatenay-Malabry, France

Abstract

A Nanosecond Repetitively Pulsed Plasma (NRPP) produced by electric pulses of 10 kV during 10 ns at a frequency of up to 30 kHz has been used to stabilize and improve the efficiency of a 25-kW lean premixed propane/air flame at atmospheric pressure. We show that, when placed in the recirculation zone of the flame, the plasma significantly increases the heat release and the combustion efficiency, thus allowing to stabilize the flame under lean conditions where it would not exist without plasma. Stabilization is obtained with a very low level of plasma power of about 75 W, or 0.3 % of the maximum power of the flame. In addition, we find that at high flow rates, where the flame should normally extinguish, the NRPP allows the existence of an intermittent V-shaped flame with significant heat release, and at even higher flow rates the existence of a small dome-shaped flame confined near the electrodes that can serve as a pilot flame to re-ignite the combustor. Optical emission spectroscopy measurements are presented to determine the temperature of the plasma-enhanced flame, the electron number density, and to identify the active species produced by the plasma, namely O, H and OH.

Introduction

Plasma-enhanced combustion is an innovative concept for improving the ignition, efficiency, and stability of industrial combustors such as aircraft engines, ground gas turbines or internal combustion engines. However, the power required to produce the plasma is a key issue for practical applications.

It has been known for a long time that high voltage pulses are an efficient way to generate active species (i.e. ionized, dissociated and electronically excited species) in air or air/fuel mixtures. Over the past several years, various researchers[1-5] have applied this technique to the ignition of fuel/air mixtures. It has been shown, in particular, that the ignition delay time can be significantly reduced through the use of nanosecond high voltage pulses[6-9].

There are however much fewer studies to date on plasma-assisted flame stabilization. To stabilize the flame, the plasma must be sustained for a relatively long duration, which requires in general a large amount of power. Recently, Choi et al.[10] were able to stabilize and extend the flammability of a lean propane/air mixture at atmospheric pressure by using a repetitive discharge at 9 kHz, with voltage pulse duration of order 100 µs. With this system, they have demonstrated the stabilization of relatively low power flames (up to about 300 W) with a plasma power consumption equivalent to about 5% of the power of the flame.

Over the past few years also, researchers from Stanford University[11] have proposed and demonstrated the use of high voltage nanosecond pulses with high repetitive frequency determined by the rate of recombination of active species, as a way to efficiently produce and sustain elevated electron number densities in atmospheric pressure air plasmas. In the present work, we employ a similar high frequency nanosecond discharge to stabilize a lean propane/air flame at atmospheric pressure.

The first part of this paper describes the experimental set-up. The second part presents a mapping of the operating regimes of a propane air/flame, with and without plasma enhancement. The third part describes the results of preliminary spectroscopic and imaging studies of the flame with and without plasma enhancement.

Experimental Setup

Nanosecond repetitively pulsed plasma

A nonequilibrium plasma is produced using a solid state generator. An electric pulse of 10 kV in amplitude and 10 ns in duration is created at a repetitive frequency of up to 30 kHz. It has been shown in previous studies[11] that such a device can sustain an atmospheric pressure discharge in preheated air with an average electron concentration of about 10^{12} cm^{-3}. The power consumption of this nonequilibrium plasma is low in comparison with the consumption of a plasma with the same electron concentration created by a dc electric field. In the present work, the energy supplied to the flame has been determined from the electric field, measured with a high voltage probe (Lecroy PPE 20kV), and the current through the electrodes, measured with a Pearson Coil (Model 2877). The energy provided to the discharge is 2.5 mJ, corresponding to an average power of 75 W at 30 kHz repetition frequency. This power is much less than the typical heat release power of flames of practical interest, usually several kilowatts. The plasma generator is powered by a DC power supply (Delta Electronika Model ES 300-0.45). The DC power supply delivers less than 100 W to the plasma generator, corresponding to efficiency greater than 75% of the pulse generator. All experiments presented in the following sections were performed with a pulse generator frequency fixed at 30 kHz.

Premixed burner

The flow rates of air and propane are controlled by flow meters with maximum flow rates of 25 m^3/h and 1 m^3/h respectively. These flow rates result in a maximum heat release of about 25 kW.

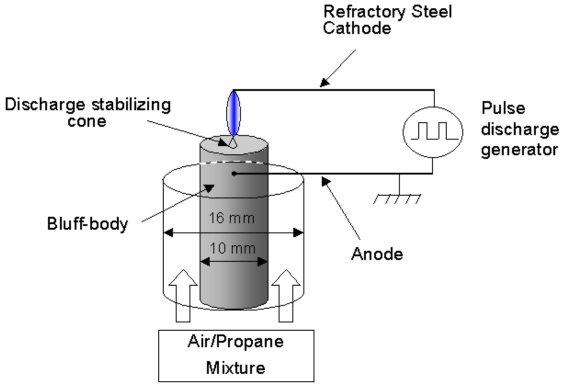


Fig. 1. Bluff-body nozzle

Different nozzles can be used to study the effect of the plasma on various flames. In this study, an unconfined bluff-body stabilized flame is investigated. The cylindrical bluff-body (figure 1) stabilizes a classical "V-shaped" premixed flame. The external diameter of the burner outlet is 16 mm and the diameter of the bluff-body is 10 mm. The Reynolds number, based on the diameter of the burner outlet and the bulk velocity, is about 30,000. The bluff- body is made of aluminum and the cathode is made of refractory steel. No erosion was noticed over operation times of several hours.

In this configuration, depending on the value of the pulse voltage, the discharge presents two regimes in the flame: a glow and a streamer regime. At low pulse voltage, the discharge is a diffuse glow discharge similar to the discharge studied in Ref. 11. At higher pulse voltage, the discharge becomes filamentary and very luminous, which corresponds to a streamer regime. In our experiments to date, the enhancement of combustion was only achieved with the streamer mode, as explained in the following sections.

Operating regimes of the flame with and without plasma enhancement

Measurements have been made of the operating regimes of a propane air combustor at atmospheric pressure, as a function of the fuel equivalence ratio and the flow rate of air. Three operating regimes can be identified in Figure 2:

- Stable V-shaped flame (region 1)
- Pilot flame (small dome-shaped flame confined to the vicinity of the electrodes placed in the recirculation zone, region 2)
- No flame (region 3)

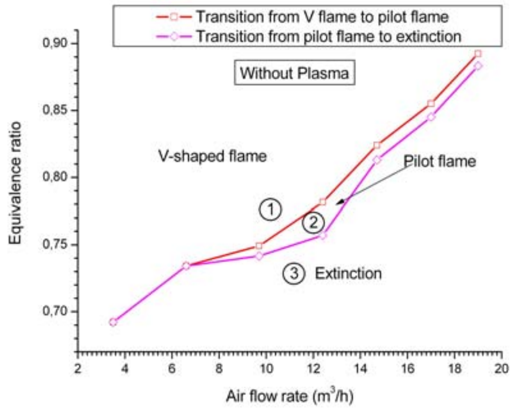
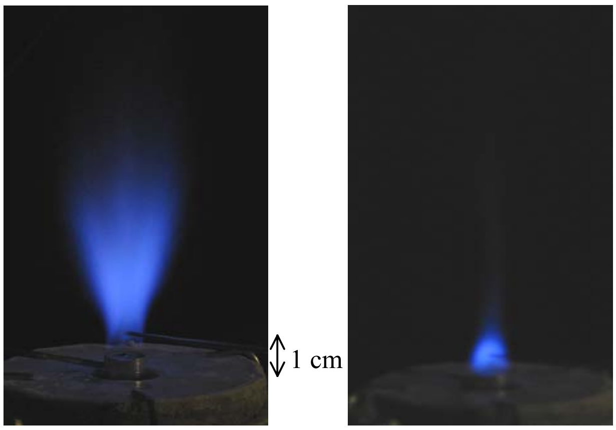


Fig. 2. Burner regimes without plasma

Figure 3 shows photographs of the V-shaped and pilot flames.



(a) (b)

Fig. 3. (a) V-shaped flame
(b) pilot flame

The main regime is a V-shaped flame stabilized on the bluff-body (region 1 in Figure 2). Increasing the air flow rate, for a constant flow rate of propane, leads to lean extinction (region 3). At high air flow rate (about 6 m^3/h) this extinction appears after an intermediate dome-shaped flame regime, which we term a pilot flame. In the latter regime, the flame is confined to the recirculation zone where the characteristic time of the flow is sufficiently low to match the characteristic time of the chemistry. This leads to a low efficiency flame, close to lean blow-off, that does not burn all the available fuel.

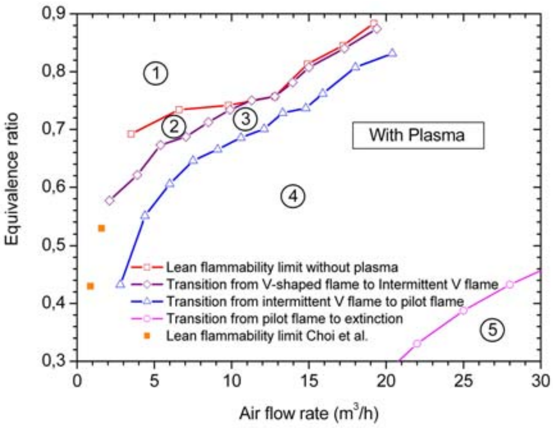
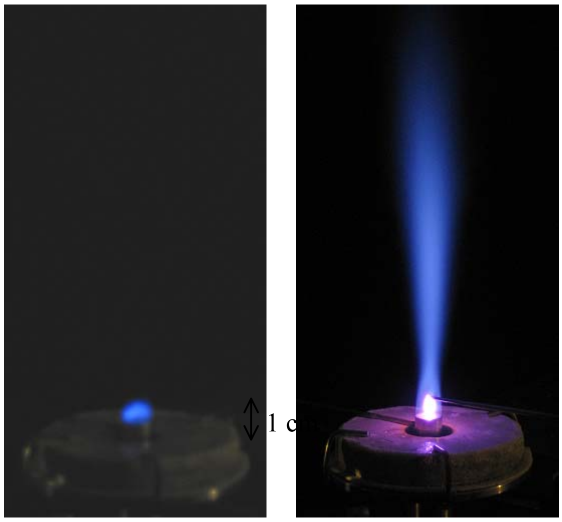


Fig. 4. Burner regimes with plasma

As can be seen in Figure 4, the plasma significantly extends the region of flame stability. For purposes of comparison, this figure also shows the extinction limit without plasma. Below this square curve, the flame does not exist without the plasma. Region 2 is an extension of the V-shaped flame below the lean flammability limit for airflow rates up to 12 m^3/h. Above 12 m^3/h, the V-shaped flame is extended over a smaller region. The diamond curve represents the transition between a fully developed V-shaped flame and an intermittent V-shaped flame. Although this regime is intermittent, the flame in region 3 still releases a significant level of heat. The triangle curve is the transition between the intermittent V flame and the pilot flame (region 4). This pilot flame can exist with the plasma over a much wider range of fuel equivalence ratios and flow rates than without plasma, which can be useful to re-ignite the combustor at low regime. The circle curve represents the lean flammability extinction limit of the flame with plasma.

Figure 5 presents photographs of a pilot flame with an air flow rate of 15 m^3/h and a propane flow rate of 0.5 m^3/h (Φ=0.8, flame power: 12.5 kW). Figure 5a shows the flame without plasma, figure 5b with the NRPP discharge (discharge power: 75W) applied. It is clear that the plasma significantly increases the combustion efficiency in very lean propane/air flames with only a small fraction of the flame power.



a b

Fig. 5. Photographs of a 12.5 kW propane/air flame (Φ=0.8) with and without plasma

Optical diagnostic measurements

Time-resolved spectroscopy of the plasma with and without flame

The foregoing results demonstrate that a low power NRPP represents an effective and energy efficient method to stabilize a turbulent bluff-body flame. However the physico-chemical processes leading to the observed combustion enhancement are not yet understood. To determine the species involved and the chemical or thermal nature of the process, we have performed spectroscopic measurements synchronized with the discharge. Figure 6 shows the experimental setup comprised of an Acton SpectraPro 2500i spectrometer (focal length 500 mm) fitted with a 1024x1024-pixel

ICCD camera (Princeton Instrument PIMax) and an imaging fiber adapter (Acton FC-446-010) combined with an optical fiber (Acton LG-4550-020). Two off-axis parabolic mirrors are used to collect the signal and to focus it on the optical fiber. These mirrors are preferred to spherical lenses to avoid chromatic aberrations. A delay generator (Berkeley Nucleonics Model 555) triggers the pulse generator and the camera to record spectra between two consecutive pulses.

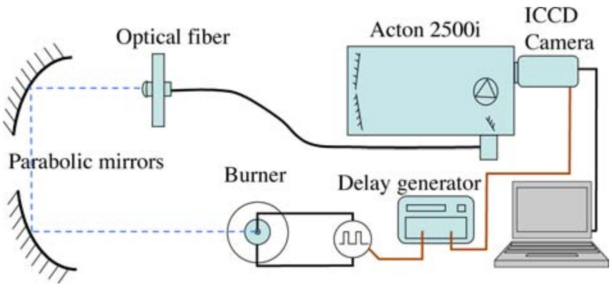


Fig. 6. Experimental setup of synchronized spectroscopic measurements

We have performed spectroscopic measurements of OH, H_β and O with and without flame. Figures 7 and 8 present measurements obtained with an integration time of 100 ns immediately after the pulse. OH, H_β and O appear to be produced by interactions between the plasma (in the streamer mode) and the flame. OH radicals and O and H atoms are key species for the initiation of combustion as they are the principal species responsible for breaking C-H bonds in hydrocarbon fuels[12]. They also accelerate the chain branching reactions of propane combustion.

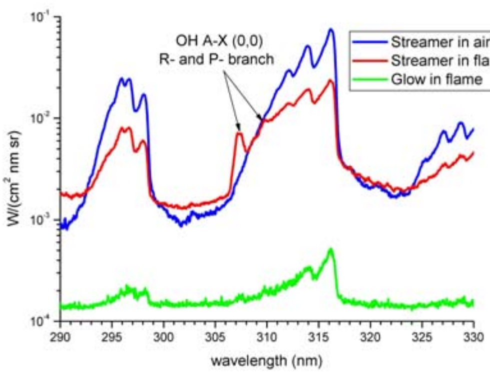
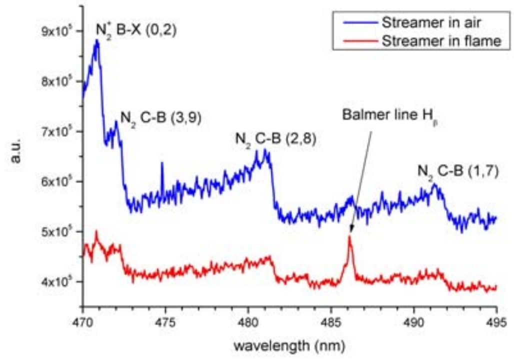


Fig. 7. Time-resolved calibrated spectrum of the streamer discharge in air and flame and of the glow discharge in flame



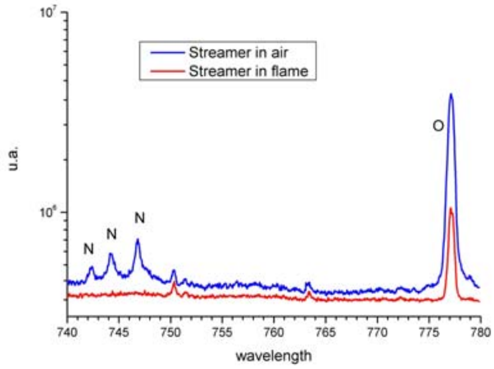


Fig. 8. Time-resolved spectrum of the streamer discharge in air and in flame.

Thermal and Chemical Effects of the Plasma Discharge

As shown in an earlier publication[15], the rotational and vibrational temperatures averaged over a time window spanning several pulses are about 2700 K and 4000 K, respectively, in the streamer discharge. Thus the streamer discharge in flame heats the gas whereas the glow discharge does not increase the gas temperature.

We present here new investigations of the time dependence of this thermal effect. Spectra of the N_2 C-B (0,2) and (1,3) bands (365 – 385 nm) have been recorded using a 1200 groove/mm grating blazed at 300 nm. The spectra have been calibrated in absolute intensity by means of a 1 kW argon mini-arc source traceable to NIST standards.

We recorded spectra with an exposure time of 5 ns. These measurements are time-resolved with a time step of 5 ns for N2 C-B. The optical train is focused onto the discharge region, at midpoint between the electrodes. The signal is averaged over 1500 pulses. We recorded the emission spectrum of a propane/air flame ($\phi = 0.8$) with a streamer discharge applied. Figure 9 presents the experimental spectra taken between 18 and 33 ns after the beginning of the pulse. The spectra are normalized to the intensity of the (0,2) bandhead. We find that the rotational and vibrational temperatures are approximately constant over that time interval.

These experimental spectra were fitted with numerical simulations obtained with the SPECAIR code[14]. The resulting rotational temperature is about 2500 K and the vibrational temperature is about 4300 K.

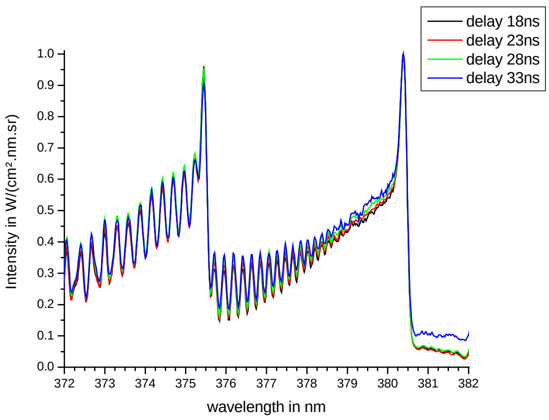


Fig. 9. Time-resolved calibrated spectrum of the streamer discharge in flame

High-resolution measurements of the H_β Balmer line

Measurements were also made of the H_β Balmer line at 486.1 nm to determine the electron number density in the discharge. As done in Ref. 16, we infer the electron number density from the half-width-at-half-maximum (HWHM) of the measured Stark-broadened line.

We used a 2400-groove/mm grating blazed at 300 nm and took time resolved measurements between 25 and 47 ns after the beginning of the pulse. The HWHM of the Balmer-β line is constant within 15 %. The exposure time was 2 ns and acquisitions were taken every 2 ns. The optical train is focused, as previously described, on the region of maximum intensity of H_β emission. The instrumental HWHM was 0.09 Å. We find that the electron number density is comprised between 10^{15} and 2.10^{15} cm^{-3}.

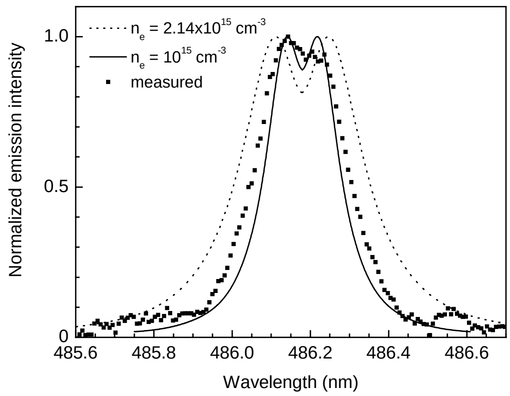


Fig. 10.measured and simulated spectrum of H_β line

We have also made 100-ns averaged measurements and compared them with simulations taken from Ref. 17. Assuming that there is no self-absorption, we obtain the same density as with the previous method. Figure 10 presents the comparison between a spectrum taken in the center of the discharge and simulations at various electronic densities. The measured spectrum suggests an electron number density of about $1.2 \pm 0.2 \times 10^{15}$ cm^{-3}.

Conclusions

We have demonstrated the possibility to increase the combustion efficiency of a lean premixed turbulent flame at low energy cost (less than 0.6 % compared to the power of the flame) through the use of a high repetition rate nanosecond pulsed discharge in the recirculation zone behind the bluff body. The repetitively pulsed discharge affords an extension of the stability of the V-shaped flame. At higher air flow rates or lower equivalence ratio, where non-assisted flame would normally extinguish, we have found that an intermittent V-shaped flame with high heat release can exist. At yet even higher air flow rates the plasma allows the existence of a pilot flame up to very high flow rates and lean conditions. Through spectroscopic measurements, we have evidenced an increase of the concentration of free radicals in the flame, which may explain the observed enhancement of combustion. The rotational temperature, measured to be approximately 2500 K after the pulse, indicates that the discharge has some thermal effect. We also determined the electron number density from the H_β-Balmer lineshape just after the pulse and obtained a value of about 10^{15} cm^{-3}.

Acknowledgments

The authors gratefully acknowledge Snecma Moteurs and CNRS for support of the present work through the INCA program (Initiative en Combustion Avancée).

References

[1] V. Chernikov, A. Ershov et al, *39th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA Paper 2001-294, Reno, NV, January 8-11, 2001.

[2] S.M. Starikovskaia, N.B. Anikin, et al, *Plasma Sources Sci. Technol.*, Vol. 10, pp 340-355, 2001.

[3] I.I. Esakov, L.P. Grachev et al, *Conference on Plasmas for Stealth and Flow and Combustion Control*, Paris, France, March 31 and April 1.

[4] V. Jivotov, B. Potapkin, et al, *Proceedings of the 2nd Workshop on Magneto-Plasma-Aerodynamics in Aerospace Applications*, Moscow, Russia, pp. 351-354, April 5-7, 2000.

[5] A. Klimov, V. Brovkin, et al, *39th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA Paper 2001-0491, Reno, NV, January 8-11, 2001.

[6] S. M. Bozhenkov, S. M. Starikovskaia, et al, *41st AIAA Aerospace Sciences meeting and Exhibit*, AIAA Paper 2003-876, Reno, Nevada, January 6-9, 2003.

[7] N. B. Anikin, E. N. Kukaev, et al, *42nd AIAA Aerospace Sciences meeting and Exhibit*, AIAA Paper 2004-833, Reno, Nevada, January 5-8, 2004.

[8] E. I. Mintoussov, S. V. Pancheshnyi, et al, *42nd AIAA Aerospace Sciences meeting and Exhibit*, AIAA Paper 2004-1013, Reno, Nevada, January 5-8, 2004.

[9] J. B. Liu, P. D. Ronney, et al, *41st AIAA Aerospace Sciences meeting and Exhibit*, AIAA Paper 2003-877, Reno, NV, January 6-9, 2003.

[10] W. S. Choi, Y. Neumeier et al, *42nd AIAA Aerospace Sciences meeting and Exhibit*, AIAA Paper 2004-982, Reno, Nevada, January 5-8, 2004.

[11] C. H. Kruger, C. O. Laux, et al, *Pure Appl.Chem.*, Vol.74, No.3, pp.337–347, 2002.

[12] W. C. Gardiner, *Combustion Chemistry,* Springer-Verlag, 1984.

[13] J. L. Jauberteau, I., Jauberteau, et al, *New Journal of Physics*, Vol. 4, No 39, pp 39.1 - 39.13.

[14] C.O. Laux, *von Karman Institute Lecture Series*, 2002-07, Physico-Chemical Modeling of High Enthalpy and Plasma Flows, *eds.* D. Fletcher, J.-M. Charbonnier, G.S.R. Sarma, and T. Magin, Rhode-Saint-Genèse, Belgium, 2002 (55 pages).

[15] D. Galley, G. Pilla, et al, *43rd AIAA Aerospace Sciences meeting and Exhibit*, AIAA Paper 2005-1193, Reno, Nevada, January 10-13, 2005.

[16] C.O. Laux, T.G. Spence, et al, *Plasma Sources Sci. Technol.*, Vol. 12, pp 125-138, 2003.

[17] M.A. Gigosos, M.A. Gonzales, et al, Spectrochimica Acta part B, 58 (2003) 1489.