Enhancement of the lean stability and blow-off limits of methane-air swirl flames at elevated pressures by nanosecond repetitively pulsed discharges

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Abstract
This paper examines the ability of nanosecond repetitively pulsed (NRP) plasma discharges to improve stabilization and extend the blow-off limit of lean premixed methane-air swirl flames at pressures up to 5 bar. The effect of two discharge regimes, NRP glows and NRP sparks, was investigated. The electrical characterization of the discharges was performed and direct images at 60 Hz of the flames, with and without NRP discharges, were collected to assess the effect of the discharges on flame stabilization. Results showed that NRP discharges efficiently extended the lean blow-off and stability limits of premixed methane-air swirl flames, at pressures up to 5 bar. These results were obtained for a ratio of NRP discharge power to flame thermal power of 0.7% or less. Moreover, the peak voltage necessary to maintain constant this power ratio did not increase linearly with increased pressure, even though the reduced electric field should linearly decrease with the pressure. It was also observed that the relative effectiveness of the NRP glows and NRP sparks changed by increasing the pressure. Based on discharge physics and current knowledge of the effect of pressure on the electrical properties of flames, explanations for these results are proposed.

Supplementary material for this article is available online

Keywords: flame stabilization, non-equilibrium plasma discharges, plasma-assisted combustion, plasma-flame coupling
(Some figures may appear in colour only in the online journal)

1. Introduction
The reduction of pollutant emissions and fuel consumption of combustion-based systems is a major challenge that is mobilizing the efforts of the scientific community. Strategies like burning lean mixtures, or increasing the pressure of the combustion chamber, have become commonplace. However, one of the limitations of these strategies, in burners and gas turbine engines, is the combustion stability [1]. Preventing unstable combustion and flame blow-off, which could fail the entire system, is crucial.

Non-thermal plasma, produced by nanosecond repetitively pulsed (NRP) discharges, has been successfully tested to
stabilize flames and extend the blow-off limit to higher bulk flow velocities or lower equivalence ratios [2–10]. However, all these studies were carried out at atmospheric pressure or below, while many types of combustors operate at elevated pressures to increase power density and efficiency. Recently, Kim and Cohen [11] showed that NRP discharges could decrease the lean blow-off limit of methane-air jet flames at pressures up to 5 bar. They reported that the extension of the lean blow-off limit at 5 bar was twice smaller than at 2 bar, suggesting that the plasma actuation was decreasingly effective with increasing pressure. As they did not provide any characterization of the discharges (optical or electrical), it was difficult to draw any conclusion on the plasma efficiency as well as on the stabilization mechanism. Therefore, their conclusions could not be extended to other types of combustion configurations, such as for example swirl-stabilized flames [9], or other plasma actuation strategies, such as for example plasma actuation in the recirculation zone [6].

In parallel to the flame stabilization studies, NRP discharges have shown promising results in plasma-assisted ignition (PAI) of combustible mixtures [12–21]. These studies showed that NRP discharges could be an effective way to decrease the lean flammability limit, minimum ignition energy, and ignition delay time. They investigated a wide range of pressures, from sub-atmospheric to elevated pressures, that mimics the operating conditions of commercial devices. The results obtained were usually attributed to a combined thermal and chemical effect of the discharges, or a hydrodynamic enhancement of the mixing [22, 23]; these effects could also be relevant for lean combustion stabilization. Therefore, it might be expected that non-thermal plasma produced by NRP discharges could have a positive impact on combustion stabilization at elevated pressures.

In this context, the objectives of the present study are, first, to assess whether NRP discharges can enhance the lean stability and blow-off limits of premixed swirl flames at pressures up to 5 bar and, second, to determine which regime of the NRP discharges is more effective in the range of the pressures studied.

2. Experimental setup and methodology

The experiments were performed in a swirl-stabilized burner integrated in a high-pressure vessel. This high-pressure test rig was designed to allow plasma actuation of the flame. It is therefore referred as the high-pressure plasma-assisted combustion (H-PPAC) test rig.

2.1. H-PPAC test rig

A schematic of the H-PPAC test rig is presented in figure 1(a), with a close view of the combustion chamber in figure 1(b). The flows of air and methane were controlled by thermal mass flow meters (Brooks SLA 58 Series). They were mixed four meters upstream of the combustion chamber to ensure a homogeneous mixture in the combustion area. The mixing section was characterized by an \(L/D\) ratio of around 300, where \(L\) is the length and \(D\) is the diameter of the mixing part. A radial swirler with a geometrical swirl number of 0.45 [24] was installed 50 mm upstream of the combustion chamber. The injection tube had an inner diameter of 18 mm and the flame was stabilized above a stainless steel rod 3-mm in diameter with an inverted cone profile of 6.5 mm diameter at its tip. The combustion chamber was rectangular, with a square section of \(85 \times 85 \text{ mm}^2\) and a length of 150 mm. Four perpendicular 2.5-mm-thick quartz windows permitted the visualization of the flame. This burner was installed in a high-pressure vessel, equipped with four 30-mm-thick quartz windows aligned with those of the combustion chamber. A co-flow of nitrogen, around the combustion chamber, ensured its cooling and prevented water condensation on the cold quartz windows of the high-pressure vessel. The test rig was designed to allow a maximum operating pressure of 20 bar and a maximum flow rate of reactants in the combustion chamber of 2500 slpm. For safety purposes, a rupture disk with a rated burst pressure of 24 bar was installed. A DSLR camera (Nikon D810) installed outside of the high-pressure vessel was used to investigate the stability of the flame. Images, as well as videos at 60 Hz, were recorded for each of the operating conditions.

The NRP discharges were generated between the tip of the rod and a stainless steel ring at the top of the injection tube. A close view of NRP discharges and a schematic of the electrodes configuration are presented in figure 2. The coaxial electrodes were separated by a gap of 5.75 ± 0.1 mm. The rod was connected to the positive high-voltage output of a pulser (FID GmbH, Model FPG 10-30NM10), while the ring was grounded. Electrical insulation between the electrodes was ensured by the bottom part of the burner made of ceramic (Macor). The edges of the electrodes were sharp from machining, i.e. with a radius of curvature below 100 \(\mu\)m.

Voltage was measured with a voltage probe (Tektronix P6015A), and the current was measured on the ground cable with a current probe (Pearson Current Monitor, Model 6585). A 2-GHz oscilloscope (Tektronix DPO5204B) recorded the current and voltage signals, simultaneously. The repetition rate was maintained at 30 kHz for the entire study. The characteristics of the NRP discharges were adjusted by varying the applied voltage.

2.2. Methodology

Characterization of the flame stability was performed up to 5 bar, following the procedures detailed here. After ignition of the flame at atmospheric conditions, the pressure was adjusted, with the help of a back pressure valve, until the desired value was achieved. Bulk flow velocity at the outlet of the injection tube was maintained constant for all conditions at 7.5 m·s\(^{-1}\). For example, at atmospheric pressure and for an equivalence ratio, \(\phi\), of 0.78, this bulk flow velocity was obtained for 103 slpm of air and 8.43 slpm of methane. When the desired pressure was reached, starting from a stable flame and after waiting ten minutes to reach thermalization, \(\phi\) was decreased by steps of 0.005, until blow-off occurred. Between each change in equivalence ratio, a delay of one minute was observed. For each experimental condition, the DSLR camera
recorded a ten-second video to assess the stability of the flame. Flame extinction and re-ignition events were observed while the equivalence ratio was reduced; these events were counted during the videos. When ten or more extinction events were detected, the flame was considered unstable. A different number of extinction/re-ignition events might be chosen to define the stability limit, but this will only affect the range of equivalence ratios between the stability and the blow-off limits, which is not the focus of this study. The general trend of the effect of pressure on the results would not be altered.

The effect of NRP discharges on flame stability and blow-off was investigated for each pressure. Two regimes of NRP discharges were tested, the NRP glow regime, and the NRP spark regime, as defined in [25, 26]. For the NRP glows, the thermal and hydrodynamic effects of the discharges can be considered negligible (see for example [27]), consequently promoting the chemical impact of the plasma. On the other hand, the NRP sparks have a strong thermal and hydrodynamic effects (see for example [23, 28, 29]). For all conditions investigated, the ratio between the average power of the discharges, $P_{\text{Glow}}$ for the NRP glows, or $P_{\text{Spark}}$ for the NRP sparks, and the thermal power of the flame, $P_{\text{Thermal}}$, was kept constant.

The thermal power of the flame was evaluated by multiplying the mass flow rate of fuel that was injected in the combustion chamber by its lower heating value (50 MJ/kg for methane). First, the equivalence ratio corresponding to the transition stable-unstable flame without plasma actuation was set. Then, the NRP plasma discharges were applied continuously, and the equivalence ratio was slowly decreased, following the procedure detailed in the previous paragraph. This procedure was followed for both NRP discharge regimes (i.e. for two different applied voltages).

Examples of single-shot pictures, extracted from the collected videos, are presented in figure 3. The videos corresponding to the 3-bar cases are available in the supplementary material (stacks.iop.org/JPhysD/53/355201/mmedia). Each column corresponds to an operating pressure. The first row presents stable flames; the second row shows unstable flames. Third and fourth rows correspond to flames burning at the same equivalence ratio as the unstable flames but with NRP glows and NRP sparks actuation, respectively. A photo of the flame with NRP sparks at 5 bar was not taken due to limitation of the maximal output voltage of the pulser.

3. Results and discussion

In this section, first, the effect of pressure on the flame stability and blow-off limits is presented, without any plasma actuation. Second, the electrical characterization of the NRP discharge regimes is introduced, followed by the presentation of the effect of pressure on plasma actuation. Finally, the effect of plasma actuation on flame stability and blow-off at elevated pressure is detailed and discussed.
3.1. Effect of pressure on flame stability and blow-off

Figure 4 presents the characterization of the flame stability at pressures up to 5 bar. The empty symbols correspond to the transition between stable and unstable flame, and the filled symbols to the lean blow-off. Recall that the bulk velocity was kept constant and, consequently, the Reynolds number, Re, as well as the thermal power, $P_{\text{Thermal}}$, scaled with the pressure. At atmospheric conditions, Re was about 8,300 and $P_{\text{Thermal}} \approx 4.5$ kW, while at 5 bar, Re was about 42,000 and $P_{\text{Thermal}} \approx 20$ kW. At atmospheric pressure, the flame was stable down to $\phi = 0.765$, and the blow-off occurred at $\phi = 0.73$. When the pressure was increased, the equivalence ratio of unstable flames and blow-off decreased continuously. At 5 bar, the unstable flame and the blow-off occurred at $\phi = 0.655$ and $\phi = 0.63$, respectively.

In Strakey et al [30], the effect of pressure on the lean blow-out of a swirl-stabilized natural gas-air flame was found to be negligible. The authors found this result ‘somewhat surprising’, and they did not provide an explanation for it. The effect of pressure on the lean blow-off limit obtained in the present study could be explained by the increase of $P_{\text{Thermal}}$ with pressure, inducing an increase in the temperature of the combustion chamber. Indeed, even though the flame temperature did not change much with pressure, an increase of the burner temperature with pressure was observed (the windows glowing red). The quartz windows were cooled by the co-flow of nitrogen, but this heat removal by forced convection was not scaled up with pressure, leading to a global increase in the burner temperature.

Besides this change in thermalization, the decrease in the equivalence ratio at blow-off with increasing pressure could also be induced by changes in the Re number and flame properties, such as laminar burning velocity and thickness. Regardless of the main blow-off mechanism [31, 32], the coupling between the aforementioned parameters is complex and will not be discussed further in this study, which mainly focuses on the plasma actuation at a given pressure.
3.2. Electrical characterization of the NRP discharges

Voltage and current measurements were performed for each experimental condition, once the steady-state was reached (after 10 s of plasma actuation). Each measurement was repeated 100 times. After synchronization of the voltage and current waveforms, the energy deposited by the discharges was determined by integrating the product of voltage and total current. Examples of voltage, current, and associated energy for NRP glows and NRP sparks are presented in figures 5 (a) and (b), respectively. These measurements were performed at 3 bar, with an unstable flame ($\phi = 0.67$). Note that, as the total current was used, the instantaneous energy was not always increasing. The charge and discharge of the capacitive elements of the electrodes assembly induced fluctuations of the instantaneous energy. However, over the entire duration of a pulse, these fluctuations compensate and the constant value (after about 1.5 $\mu$s) corresponds to the cumulative energy deposited in the discharge.

The voltage, current, and deposited energy differed for the two discharge regimes. For the NRP glows (figure 5(a)), both the voltage and the current fluctuated strongly, due to multiple reflections between the electrode gap and the pulser. The energy was about 1.8 mJ per pulse, corresponding to a $P_{\text{Glow}}$ of 54 W. To keep the ratio $P_{\text{Glow}}/P_{\text{Thermal}}$ constant for all pressure, the applied voltage was adjusted for each pressure. The value of $P_{\text{Glow}}/P_{\text{Thermal}}$ was fixed at 0.32%.

For the NRP sparks (figure 5(b)), the voltage and current waveforms displayed three main peaks, spaced by about 600 ns. This was a property of the pulser and could not be adjusted. The corresponding energy and power were about 5 mJ and 108 W per pulse, respectively. To keep the ratio $P_{\text{Spark}}/P_{\text{Thermal}}$ constant for all pressures, the applied voltage was adjusted for each pressure. Note that for an applied voltage corresponding to the NRP sparks, the occurrence of a spark regime was not 100%. Some of the discharges were in the glow regime. This was taken into account in the evaluation of the average power of the NRP spark actuation. The value of $P_{\text{Spark}}/P_{\text{Thermal}}$ was fixed at 0.7%.

3.3. Effect of pressure on the plasma actuation

Because the thermal power of the flame increased almost linearly with pressure, to maintain a constant ratio of plasma power over flame thermal power, it was necessary to adjust the electrical actuation (i.e. the applied voltage), for each operating pressure. Figure 6 presents peak voltages and average energy per pulse measured for both the NRP glows and the NRP sparks, as a function of pressure. As the pulse repetition frequency of the NRP discharges was kept constant at 30 kHz, a linear increase in the plasma power corresponded to a linear increase in the energy per pulse. Figure 6 shows that this adjustment was reasonably achieved. Note that this increase of the energy per pulse with pressure corresponded to visually similar NRP discharges for each pressure (see figure 3). The actuation with NRP sparks could not be investigated at 5 bar due to the limitation of the maximal output voltage of the pulser (14.5 kV).

For both plasma actuation, the necessary applied voltage increased with the pressure, but less than expected. Indeed, the gas density increases linearly with the pressure. Therefore, to
maintain a similar reduced electric field and discharge behavior, for a fixed electrodes geometry, it is expected that the applied voltage should also increase almost linearly with the pressure. However, in this study, at atmospheric conditions, the actuation by NRP glows was obtained for a peak voltage of 7 kV, while at 5 bar, the peak voltage barely reached 13.7 kV, whereas about 35 kV would have been expected. A similar trend can be noticed for NRP sparks actuation.

Several mechanisms could be responsible for this result. First (as mentioned in section 3.1), due to scaling of $P_{\text{thermal}}$ with the pressure, the temperature in the combustion chamber increased with the pressure. This thermal change lowered the gas density and partly compensated for the effect of pressure on the reduced electric field. Second, the level of pre-ionization of the inter-electrode gap could increase with the pressure, due to an increase in the electron density of the flame. In fact, the NRP discharges were generated in a complex medium that included methane-air mixture, flame front, and burnt gases. Studies of the electron density in flames at elevated pressure would be necessary to quantify this effect. Finally as the energy deposited in the discharges increased with pressure, an increase in the electron density (as well as a potential change in the time of recombiniation) could also contribute to this non-linear effect of pressure. A more detailed analysis will be necessary to identify the main mechanisms responsible for this non-linear effect of the pressure on the peak voltage.

From a practical point of view, this result is promising for the implementation of plasma actuators at elevated pressure. For applied voltages higher than 20–30 kV, the electromagnetic interference (EMI) has the potential to become an important issue, one that should be treated with extreme care. The results presented in figure 6 suggest that standard EMI protection devices could be used during plasma actuation of conventional industrial combustion systems.

3.4. Effect of the NRP plasma discharges on the flame

The effects of NRP glows and NRP sparks on stability and lean blow-off limits, as a function of the pressure, are presented in figure 7. To aid the comparison, the results presented in figure 4 for the flame without plasma actuation are also recalled. Over the entire pressure range, the stability, as well as the blow-off limits, were extended to lower $\phi$ by both NRP glows and NRP sparks actuation. At any pressure, $\phi$ was decreased by 5 to 7% for both the stability and the blow-off limits, with respect to the flame without discharges. Compared to the results presented in [11], where it was shown that the plasma effect on the lean blow-off limit decreased with pressure, these results highlight that combustion enhancement by NRP discharges can be strongly sensitive to the actuation strategy.

At pressures up to 2 bar, the NRP sparks were more effective than the NRP glows, while at higher pressures, the NRP glows had a stronger effect on the flame stability, and produced results similar to the NRP sparks for blow-off. This change in the relative efficiency of both NRP discharge strategies, with the pressure, could be explained by a change in the main mechanisms of plasma action.

Depending on their regime, NRP discharges can affect flames through thermal, kinetic, and/or transport mechanisms [22]. For the NRP sparks, the three energy pathways are active, and they can be considered as a local source of ignition [22, 33]. On the other hand, NRP glows are known to have a negligible thermal and transport impact [25, 27], and their kinetic effect is predominant. At low pressure, the local ignitions at the outlet of the injection tube, caused by the NRP sparks, seemed to stabilize the flame better than a purely kinetic actuation. This result was expected because (i) a combined thermal-kinetic impact is usually more efficient on combustion processes than a purely kinetic actuation (see for example [34]), and (ii) $P_{\text{Spark}}$ is twice larger than $P_{\text{Glow}}$, so for a similar flame, the impact on the flame should be stronger. As the pressure was increased, the applied voltage, as well as the energy per pulse, was increased. For the NRP glows, this should have resulted in a stronger chemical effect, and possibly a small thermal impact. For the NRP sparks, a higher energy deposition could increase the ultra-fast heating of the gas (described at atmospheric pressure in [29, 35]). In this case, the expansion and shock waves following the discharge could carry enough energy to destabilize the combustion front, therefore counterbalancing the local ignition. In addition, as shown numerically in Castela et al [36], and experimentally in Stepanyan et al [37], NRP sparks can generate a pair of toroidal vortices that may have a detrimental effect on the local ignition. This detrimental effect would be enhanced by the higher energy deposition with increasing pressure.

In summary, with increased pressure, the NRP sparks became less efficient than NRP glows, probably due to the higher energy deposition generating stronger vortices, pressure and shock waves, disturbing the flame stabilization. This proposed explanation was supported by visual observations in which a stable flame was blown-off if the plasma actuation by NRP sparks became too strong, even at atmospheric pressure.
Further investigation is necessary to demonstrate this destabilization process of swirl flames by strong NRP sparks.

3.5. Comparison of the stabilization strategies

To further evaluate plasma actuation strategies, it is interesting to compare the power required to avoid flame blow-off by NRP sparks, NRP glows, and fuel addition. For a given pressure, consider the thermal power of the flame, corresponding to the lowest equivalence ratio at blow-off, which can be obtained with NRP discharges. The additional power necessary to avoid blow-off, \( \Delta \text{Power} \), is equal to \( P_{\text{Spark}} \), for the actuation by NRP sparks. In the case of fuel addition, \( \Delta \text{Power} \) is equal to \( P_{\Delta \text{Fuel}} \), which is the thermal power carried by the additional fuel rate (considering optimal combustion), which should be added to the mixture to avoid blow-off. Finally, in the case of NRP glows actuation, \( \Delta \text{Power} \) is equal to \( P_{\text{Glow}} \) for elevated pressures, and to \( P_{\text{Glow}} + P_{\Delta \text{Fuel}} \) for pressures up to 2 bar. The three different additional powers and their impact on the equivalence ratio at blow-off are illustrated in figure 7, for atmospheric pressure. Figure 8 summarizes the results obtained for 1, 2, 3 and 4 bar.

For all pressures, to obtain the same extension of the blow-off limit, it was more efficient to add power by plasma actuation than by increasing the flow rate of fuel. This trend increased with pressure. At 1 bar, it was necessary to add 6 times more power by fuel addition, compared to plasma power by NRP sparks, while at 4 bar, 12 times more power by fuel addition was necessary to obtain the same result as for plasma power by NRP glows. It is worth noting that, at elevated pressures, a lower value of \( P_{\text{Glow}} \) than \( P_{\text{Spark}} \) would have the same impact on the lean blow-off limit, whereas, at pressures lower than 2 bar, additional fuel had to be added to NRP glows to achieve the same impact than NRP sparks. Figure 8 shows that, for pressures in the 1–4 bar range, NRP discharges were always more efficient in extending the blow-off limit than increasing the flow rate of fuel. Note that this comparison does not include the efficiency of the pulser, which could mitigate this result.

4. Conclusion

The ability of NRP plasma discharges to enhance the lean stability and blow-off limits of methane-air swirl flames was investigated, at pressures up to 5 bar. The effects of two discharge regimes, NRP glows and NRP sparks, were analyzed. Main findings were:

- The peak voltage necessary for a comparable plasma actuation of the flame, at constant bulk flow velocity, did not scale linearly with pressure. For both NRP glows and NRP sparks, at 4 bar, peak voltages were less than twice of those corresponding to atmospheric conditions.
- The NRP discharges effectively extended stability and blow-off limits for all the pressures considered. At pressures higher than 2 bar, the NRP glow discharges appeared to be more efficient than the NRP sparks. This result was opposite to that obtained at atmospheric pressure in this study as well as in the literature.
- In terms of stabilization strategy, it was more energy efficient to avoid the blow-off of a flame by adding NRP discharges, rather than increasing the flow rate of the fuel.

These results are promising for the control of flame stability by non-thermal plasma at elevated pressures. However, they also emphasize that investigations of plasma-assisted combustion at pressures relevant to industrial applications are necessary. Indeed, a simple extrapolation of the results obtained at atmospheric pressure would produce erroneous results.

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