Actuation of a premixed stagnation flame by nanosecond-pulsed plasma at atmospheric pressure
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Abstract: This study presents the effect of nanosecond repetitive pulsed (NRP) discharges on a lean premixed methane-air flame at atmospheric pressure. The effect of the pulse repetition frequency (PRF) of the plasma on the flame was studied with time-resolved imaging of the flame emission and shows that at higher PRF, the flame stabilizes upstream in the unburnt mixture. This actuation of the flame using nanosecond-pulsed plasma suggests a potential method to control flame speed with NRP discharges.

Keywords: Plasma assisted combustion, nanosecond pulsed discharge, stagnation flame.

1. Introduction

NRP discharges are of increasing interest in combustion-based applications due to their ability to improve ignition, flame stability, combustion efficiency, and reduce emissions. This is explained by the fact that NRP discharges release heat and generate reactive species in a time scale and temperature window which combustion itself cannot achieve. NRP plasma discharges can increase flame reactivity via three different mechanisms: thermal, kinetic and transport pathways. Since these pathways are coupled together, it is necessary to study the effect of plasma on flames in well-controlled experiments in order to clearly isolate and understand the related basic physical and chemical mechanisms [1].

2. Experimental

This study presents the effect of a diffuse non-equilibrium nanosecond-pulsed plasma on a lean premixed methane-air flame with an equivalence ratio of 0.75 and total flow rate of 20 SLPM (standard litres per minute) at atmospheric pressure. The apparatus consists of a slot burner capable of generating a flat flame stabilized by a stagnation plate. Two pin electrodes are used to actuate the optically accessible flat flame by generating NRP discharges upstream of the flame front, which leads to a displacement of the flame further upstream in a high velocity region of the flow, as shown in Fig. 1, which is evidence of an increased flame speed.

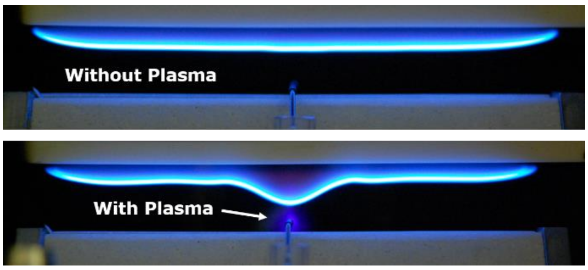

Fig. 1. Plasma-assisted flame in slot burner

The plasma is generated using a custom-built pulse generator based on a previous iteration presented in [2]. The novel pulse generator uses pulse transformers and fast recovery diodes to produce high voltage pulses with an amplitude of 8.5 kV and a duration of 80 ns FWHM (full-width at half-maximum) at a PRF of up to 6 kHz. The generated voltage pulse is presented in Fig. 2 along with the pulse energy for a PRF of 1 kHz. The pulse energy is obtained by integrating the pulse voltage multiplied by the conductive current. The conductive current is obtained by subtracting the displacement current from the total current and the displacement current is calculated by properly matching the capacitance constant of the time derivative of the voltage signal with the capacitive signal of the measured total current.

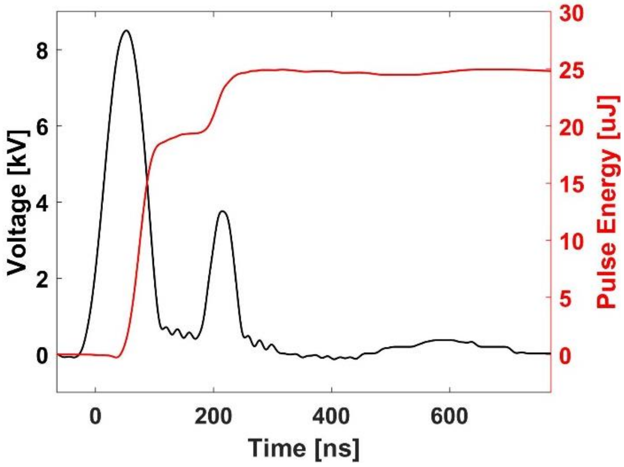

Fig. 2. Pulse voltage and pulse energy for a PRF of 1 kHz

3. Results

The flame displacement was measured using intensified charge-coupled device (ICCD) imaging. The effect of the plasma PRF on the flame was studied with time-resolved imaging of the flame light emission by taking the average of 500 frames obtained by 250 exposures of 100 ns. Each exposure is taken at some specific time between two consecutive pulses to increase the signal to noise ratio. Fig. 3 shows the leading edge of the flame for various PRF. The first two columns are related to a delay of 200 ns and 1 µs after the pulse, while the last column shows the results after a delay that corresponds to the last picture that can be taken before a new voltage pulse is applied. The horizontal red lines show the location of the upstream leading edge of the flame. From these results, we observe that the flame remains steady and does not relax in between two consecutive pulses.

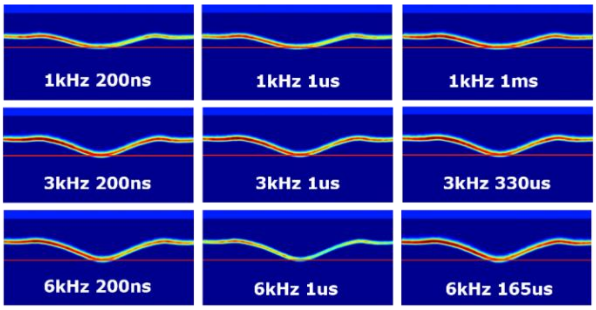

Fig. 3. Flame displacement for various PRF after 200 ns, 1 µs and right before the following discharge

This method is repeated for different PRF ranging from 1 to 6 kHz and the results are presented in Fig. 4 where the upstream displacement of the leading edge of the flame is shown again for different delays between two pulses. From these results we observe that, as the PRF increases, the flame stabilizes further upstream in the unburnt mixture which shows an increase of the flame speed with PRF. The relatively high error bars associated with the data presented in Fig. 4 are due to the variation of the voltage pulse (8.5 ± 0.1 kV) during the acquisition of the exposures which lead to an uncertainty of ± 0.2 mm on the displacement of the leading edge of the flame.

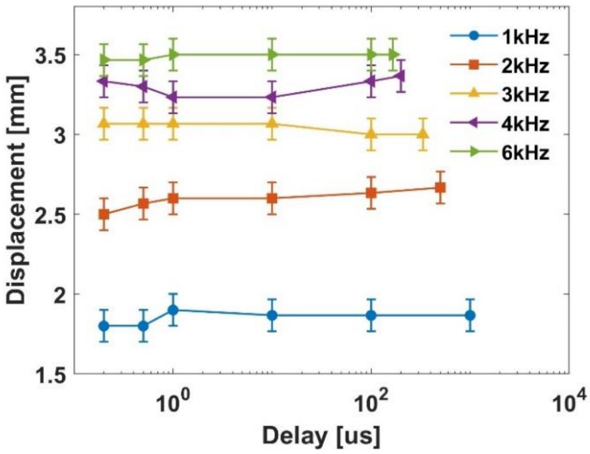

Fig. 4. Flame upstream displacement for various delays between two consecutives discharges

Pulse energy measurements were made for each PRF presented in Fig. 4 following the methodology presented in section 2 and Fig. 2 to determine the total power required to produce the plasma and actuate the flame. The resultant power is then compared to the total thermal power of the actuated section of the flame to obtain the percentage of the flame thermal power necessary to observe the displacement of the leading edge of the flame. This is shown in Fig. 5 where we observe that a maximum of 0.5% of the flame thermal power needs to be injected to observe the maximum upstream displacement of the flame. This suggests that NRP discharges can potentially be used to control flame speed, as the upstream displacement of the flame means that the flame is stabilized in a higher velocity region of the flow and which is also evidence of enhanced flame speed.

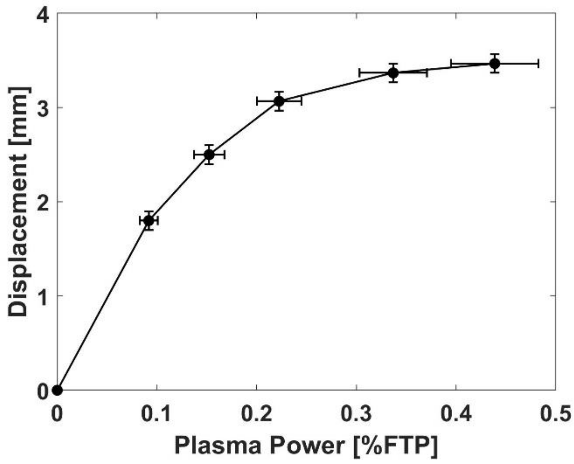

Fig. 5. Percentage of the flame thermal power (FTP) required to produce the observed displacement

4. Conclusion

Hence, the use of NRP discharges to actuate a flat premixed flame produced by a slot burner shows a much cleaner effect than what was previously presented in [3]. Indeed, the actuation in [3] showed a distorted flame which makes difficult to identify if the actuation of the flame is caused by the kinetic and thermal effects or a hydrodynamic effect of the plasma. In future work, particle image velocimetry will be implemented in the current apparatus to measure the velocity field of the flow and to characterise the increase in flame speed produced by NRP discharges. This apparatus will also greatly simplify the implementation of advanced optical diagnostics to make relevant measurements in well-defined experiments in order to better understand the underlying mechanisms leading to the actuation of the flame.

5. References

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