Pulsed helium-based multijets as a new approach for flame control

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Abstract: Innovative technology was designed for plasma enhanced premixed flame studies. The effect of a plasma multi-jets (PMJ) on CH_4-Air premixed laminar flat flame is investigated. This study mainly focuses on the measurement of flat flame position and analysis of emission spectra for various conditions. The PMJ have a strong impact on the flame features, leading to a significant upstream shift of the flat flame. That confirmed the possibility of flame efficient control at very modest plasma input power.

Keywords: Plasma multijets; Flame stabilization; Lean premixed flat flame; Duty cycle

1. Introduction

Plasma-assisted combustion systems have garnered increasing interest in a wide range of experimental research projects. The interest to use plasma rises due to the continuous progress of plasma efficiency and better plasma monitoring and understanding. As a promising technology, non-equilibrium plasma can improve flame reactivity through thermal, kinetic, and transport effects [1]. With the thermal effect, the plasma raises the temperature, increasing chemical reactivity and speeding up fuel oxidation [2]–[4]. Nanosecond repetitively pulsed discharges and gliding arcs have among the greatest outcomes for different aspects of combustion enhancement at atmospheric pressure. The kinetic enhancement pathway involves the production of electrons, ions, radicals, and excited species via electron impact ionization, dissociation, and excitation, which favors faster fuel oxidation methods over slower chemical reactions [5]–[7]. The effect of diffuse non-equilibrium nanosecond-pulsed plasma at atmospheric pressure on a lean-premixed CH4-air flame was studied [8] and showed that the flame moves upstream and stabilizes in the region of high level excitation species. According to spectroscopic measurements, the observed actuation is most likely caused by reactive species migrating to the flame front [8].

Due to these advantages, plasma has been extensively applied in multiple studies to control various flames. A broad variety of fuels have been investigated both in premixed and non-premixed flames based on the equivalence ratio, pulse repetition rate, and power deposited in plasma discharge, these publications suggest that plasma is promising for combustion systems, affecting the flame geometry [2], extending the lean blow-off limits, and improving the burning velocity [9]. Almost all of them are focused on the stabilization of lean flames, the reduction of ignition delay time [3], the extension of flammability limits [1], and the increase of burning velocity [10].

A recent study based on a plasma manipulation of a diffusion flame system investigated the effect of burst mode on plasma-assisted flame stabilization [11]. The presented results showed that burst mode can achieve similar beneficial effect on flame control and stabilization while requiring less energy than continuous mode.

All these studies use combustion systems specially designed for use in combination with a plasma. With the aim to achieve plasma-induced action on premixed flame with high energy efficiency without any modification of the burner, we introduce in this work a new non-thermal plasma device at atmospheric pressure, namely plasma multijets. Beyond the already demonstrated non-thermal plasma action on the flame with other plasma device, plasma multijets offer two key advantages. They can be designed with geometry suitable for a wide variety of burners and they can be generated inside the premixed reactive flows, while being independent from the burner body. This later point meaning, plasma multijets may be less intrusive than other discharge setups.

This study targets the preliminary assessment of a He and He mixture plasma multijets produced upstream of a lean premixed methane-air flat flame at atmospheric pressure. After demonstrating that plasma multijets are likely to induce significant action on the flame, a special focus is addressed on the key role of the discharge duty cycle of He and He mixture (He/N_2 and He/N_2/O_2) plasma multijets.

2. Experimental set up

The experiments were conducted with a premixed Bunsen-type burner schematically presented in (Fig. 1). Inside the burner a metal injector with six orifices (orifice diameter dorifice = 200 µm) serving as plasma reactor is mounted along the central axis (z-axis of Fig. 1), 46 mm under the nozzle exit (nozzle diameter dnozzle = 15 mm). A pulsed high voltage generator is used to power the discharge. The high voltage electrode is connected to the metal injector while the burner body is grounded as sketched in Fig.1

A metallic stagnation plate is placed 25 mm downstream from the burner. The fuel was chemically pure grade methane (CH_4 N45) and compressed air was used as an oxidizer. The equivalence ratio, Φ, is defined as:

$$\emptyset = \frac{\left(\frac{\dot{n}_{CH4}}{\dot{n}_{O2}}\right)}{\left(\frac{\dot{n}_{CH4}}{\dot{n}_{O2}}\right)_{st}} \quad (1)$$

In (1), $\dot{n}_{CH4}$ and $\dot{n}_{O2}$ are the molar flow rates of CH_4 and O_2, respectively, and $(\dot{n}_{CH4}/\dot{n}_{O2})_{st}$ is the stoichiometric ratio needed for complete combustion.

A reactive mixture of methane, air and helium (or He mixture) at an equivalence ratio of 0.81 to 0.84 for a global flow of 3.7 $L.min^{-1}$ flows through the nozzle exit. Giving as a result a stable premixed stagnation plate flame between the stagnation plate and the nozzle exit of the burner, in the velocity field where the laminar flame speed equals to that of the unburned reactive mixture. To ensure a steady flame, the operating conditions are carefully selected.

An atmospheric helium plasma multijets is generated at the exit of the injector using a unique GREMI power supply, producing high voltage microsecond pulses of up to ±20 kVpeak with maximum actuating frequency of 30 kHz. For this study a negative polarity pulse of -12 kV in amplitude and 4 µs in duration is used with repetition rate of 20 kHz.

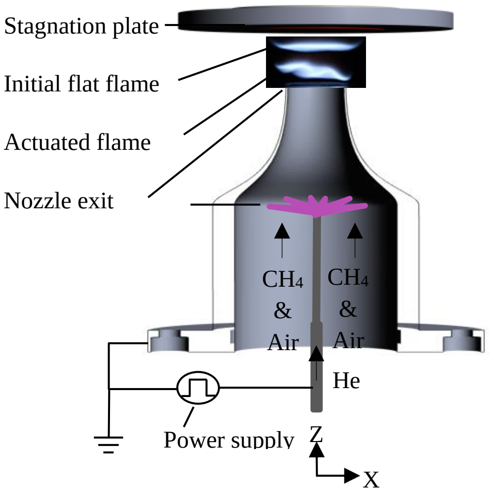

Fig. 1. Schematic representation of the burner and the plasma multi-jet devices (side view of the burner).

The discharge develop six jets with a 30° angle in the unburned reactive flow in x-axis. The pulse power generator can be slaved/controlled by a TTL generator driver. The TTL driver allows to define the duty cycle, power ON/power OFF of the discharge. The duty cycle is defined as the fraction of one period in which a system is active, expressed as a percentage or a ratio:

$$D = \left(\frac{t_{ON}}{T}\right) \times 100\% \quad (2)$$

Where D is the duty cycle, t_{ON} is plasma active time, and T is the total period of the signal. D can vary from 0 to 100%.

Fig. 1 also shows the front view of the initial flat flame (without plasma) and the actuated flame (with plasma). For the case without plasma, it is clear that the flame is flat, the flow is laminar and unaffected by the presence of the metal injector within the burner or by He flow coming from the metal injector. It is evident that after switching on the plasma the flame appears to move upstream in the flow toward the region where the plasma is being produced. The various operation mode of the multi jets allow to try and segregate the distintcs impacts of the plasma discharge on the flame features.

The displacement of the front flame is tracked over time using Canon EOS 6D Mark II camera equipped with a Canon EF50mm f/1.8 STM objective. To obtain an image representing the position of the flame at a certain time following the plasma pulses, each exposure is captured at a specific delay following the plasma pulse delivery. A video of 30s with 50 frame/s of 20 ms exposure time and a spatial resolution of 27 pixels/mm is recorded for each experimental condition and the frames are processed using MATLAB code.

3. Results and discussions

Duty cycle effect

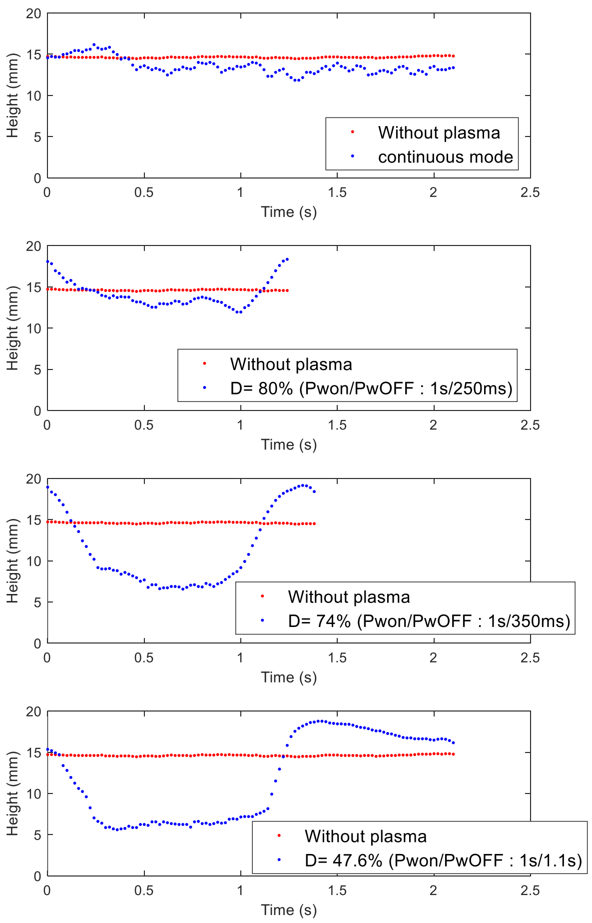

Fig. 2. Flame height without plasma (red) and with plasma (blue) at different times between consecutive pulses. (TTL cycle ON/OFF: 1s/0s (continuous mode), 1s/250ms, 1s/30ms and 1s/1.1s) (Side view of the burner).

Fig. 2 shows the flame height without plasma (red) and with plasma (blue) at different times between consecutive pulses for various pulse interruption times (TTL signal cycle t_{ON}/t_{OFF}: 1s/0s (continuous mode), 1s/250ms, 1s/350ms, and 1s/1.1s). In this experiment, the equivalence ratio is set to 0.815 with flow velocity of 0.35 $m.s^{-1}$ through the nozzle exit. From these results, we observe that for the case without plasma actuation, the height of the flame remains constant. Together the presence of the injector and the helium flow have no critical impact on the flate flame generation and stabilization. Plasma actuation results in a significant modification of the flame height, the flame appears to move upstream in the flow toward the burner. As the pulse interruption time increases $t_{OFF} \geq 350$ ms or duty cycle decreases D≤ 74%, the flame is moved further upstream during the pulses discharges and appears to flashback upward at higher position than with the non-plasma ignition steady-state position.

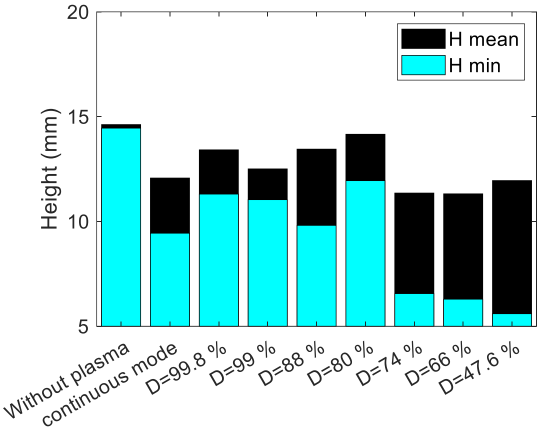

Fig. 3. Minimum flame height without plasma and with plasma (continuous mode and for different duty cycles).

Fig.3 shows the mean and the minimum of the flame height, over one period, for various duty cycles without and with plasma, (continuous mode, d=99.8% 1s/1.5ms, d=99% 1s/10ms, d=88% 1s/130ms, d=80% 1s/250ms, d=74.6% 1s/350ms, d=66% 1s/500ms, and d=47.6% 1s/1.1s). Global mean flame position shows a benefit in all plasma cases compared to without plasma. The benefit between continuous and duty cycles plasma mode occurs for duty cycle cases smaller than 75%, from 13 to 12 mm respectively. This gap increases in the range of 2 or 3 times more when the minimum flame height is analyzed. For a fixed duty cycle of 67,5%, after one second period of activation, halting the discharge for 480 milliseconds demonstrated that as the flow rate increases plasma's effect on the flame reduces, and the time delay until the flame begins to relax decreases. In addition, the flame requires a short time to fully relax to its unactuated state, which corresponds to the time needed for species to travel from the plasma zone to the flame front.

Gas mixture of plasma multijets effect

	Experimental condition (C)	Premixed flow		Plasma multijets		
		Air (L/min)	CH4 (L/min)	He (L/min)	Air (L/min)	He + 5%N2 (L/min)
He	1	2,94	0,25	0,5	0	0
He + Air	2	2,94	0,25	0,43	0,07	0
	3	2,87	0,25	0,43	0,07	0
	4	2,87	0,25	0,5	0,07	0
	5	2,94	0,25	0,465	0,035	0
	6	2,87	0,25	0,465	0,035	0
	7	2,9	0,25	0,465	0,035	0
	8	2,9	0,25	0,5	0,035	0
	9	2,94	0,25	0,5	0,035	0
He + N2	10	2,94	0,25	0,465	0	0,035
	11	2,9	0,25	0,465	0	0,035
	12	2,9	0,25	0,5	0	0,035
	13	2,94	0,25	0,465	0	0,07

Fig. 4. Experimental conditions of premixed flow and plasmamultijets working gas.

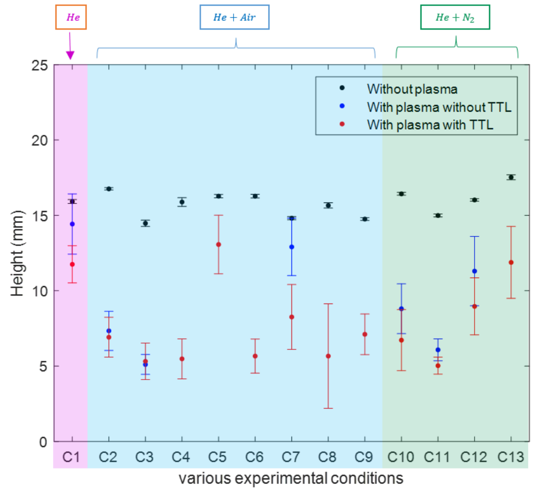

Fig. 5. Flame position without and with plasma with or without duty cycle (D=66%) for various experimental conditions (Fig 4).

Figure 5 shows the flame position for various experimental conditions detailed in Figure 4, various equivalence ratio, flows and dilution ratio. The mean position of the flame is closer to the burner with He plasma multijets actuation. The effect is amplified with the used of a duty cycle of 66% which is one of the better conditions as shown in “duty cycle effect” part. For the conditions [C2-C13], the nature of the multijets are modified by adding either nitrogen or air in small quantities, the effect on the flame position is more significant than using pure He plasma multijets. Flame position variation is at least equal or greater when using a duty cycle for all conditions.

4. Conclusion and perspectives

An experimental study of atmospheric pressure He plasma multi-jet effects on methane-air premixed laminar flat flame characteristics is performed. A simple modification of a commercial burner is used in this new technology. We embedded an injector serving as multijets plasma within a burner, such that they are able to perform plasma-assisted combustion without altering the outer configuration of the existing combustion system. The flame diluted by helium is clearly flat, hence the flow is laminar and unaffected by the injector's presence within the burner. Multijets plasma was created upstream of the flame inside the burner using a unique GREMI power supply producing voltage pulses of -12 kV at a repetition rate of 20 kHz. On the pulse power supply, a TTL cycle is adopted to generate discharges for different duty cycles while reducing energy consumption.

This setup allowed the study of the effect of duty cycle on the stability and relaxation of the flame. The experiment demonstrated that the flame position of the unsteady way is lower than that of the continuous mode. The flame stabilization ability with plasma actuation is enhanced by rising the pulse width interruption time or decreasing the duty cycle for reducing energy consumption. The influence of the duty cycle has yielded new and interesting results which should make it possible to advance in the understanding of the mechanisms of action of plasma multijets on flames.

To investigate the main cause of the flame displacement, further work will aim to investigate the kinetic effect by changing the duty cycle for various gas mixtures of the plasma jets. The chemistry of plasma multijets must also be studied. An optimization of the electrical characteristics should further increase the effect of the plasma multijets.

5. Acknowledgments

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