Atmospheric pressure plasma jet effects on a lean methane–air premixed laminar flame

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Abstract: This paper presents an investigation of atmospheric pressure plasma jet effects on a lean laminar methane-air premixed flame. This study focuses on the flame height and on the blow-off limit as a function of the equivalence ratio, with or without plasma, and as a function of the plasma pulse frequency for two flow rates. The plasma jet combined to the lean methane-air flame leads to extend the blow-off limits at low equivalence ratios. Adding plasma and increasing its pulse frequency induces a decrease in the flame height.

Keywords: plasma gun, plasma-assisted combustion, laminar flame, low equivalence ratio.

1. Introduction

Plasma-assisted combustion systems are widely spread in experimental scopes of research activities. As a promising technology, plasma-assisted combustion is an unprecedented opportunity for improving energy performance of combustion systems [1-3]. The interest to use plasma rises due to continuous progress of plasma efficiency and better plasma control and understanding. Recently, prototypes burners are designed to study the effect of various plasma type [4-7] and power sources [8-14] on combustion characteristics. These papers conclude that plasma is beneficial for combustion systems extending the lean blow-off limits and increasing the burning velocity mainly depending on equivalence ratio, pulse repetition rate and power deposited in plasma discharge. Most of them deal with stabilization of lean flames, decreasing ignition delay time, extending flammability limits and increasing the burning velocity [15-17].

This contribution reports some results of this study based on the plasma gun [18] combined with a laminar lean premixed flame [19]. Experiments performed indicate plasma benefits in term of flammability limits and flame height. Flame emission spectra are recorded to compare species produced during the combustion with or without plasma.

2. Experimental setup

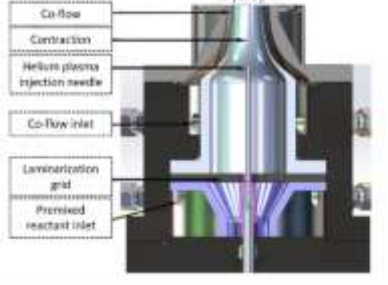

Fig. 1. Schematic of the experimental burner.

The experimental device is the combination of two setups used previously to study combustion characteristics for one and plasma gun for the second. The burner (Fig. 1.) has been adapted to allow plasma jet integration.

A laminar premixed flame is stabilized using independent flowmeters for each gas (methane and air) to control the equivalence ratio. The fuel and oxidizer premix before the burner and are introduced through the side of the burner. A so-called 'particle diffuser cone' filled with 6 mm glass beads is used to ensure a homogeneous mixture in the nozzle plenum. It is finally accelerated in the converging section with a D = 15 mm outflow diameter, creating an upward-oriented jet with a nearly top hat velocity profile at the burner exit.

The plasma of helium is generated using a coaxial dielectric barrier discharge reactor with a polyamide capillary tube beside the burner. Inside a 4 mm diameter tube is inserted a ring electrode connected to the high voltage, while a second ring electrode around the tube is connected to the ground. The two electrodes are separated across the 1 mm thick tube. The polyamide tube is connected to metal tube of 2 mm in diameter located on the centerline of the flow and 20 mm upstream the burner outlet. Thus, the helium plasma generating reactive species but also transient electric field, ignited by the external discharge reactor, is transfered through the polyamide tube and is ignited again at the outlet of the metal tube directly inside the premixed gas just before the flame area. The device was powered by a unique GREMI power supply prototype named GENEPULSE. It provides microsecond-duration voltage pulses with peak amplitude of 15.2 kV in this work, with a repetition frequency tuned from 2 kHz to 20 kHz.

Helium flow rate used to generate the plasma is arbitrary fixed at 1 $L.min^{-1}$ to not disturb the flame geometry and stability. Premixed methane/air flames were selected to conduct the present study at different equivalence ratios. The latter covers a range of 0.732-0.878 and 0.709-0.865, which represent flow rates at 0.82-1/11 $L.min^{-1}$ and 1-1.2/13 $L.min^{-1}$ respectively.
Images are captured with a Canon 400D digital camera, equipped by Canon EFS 54 mm F5.6 lens working with an exposure time of 1/13 second at ISO 800 with a field of the view of 3888×2592 pixels2. The flame height is determined using a *Matlab* routine by extracting the flame

contour. Firstly, a contrast-limited adaptive histogram equalization (CLAHE) is applied to the original images in order to optimize the contrast in the images. Then, to limit the pixelization associated with the CLAHE, images are filtered using a Gaussian filter of size equal to 4 times the spatial resolution. For the binarizing procedure, we use a standard threshold-based technique. More precisely, the histogram of the gray scale is calculated. The latter reveals two distinct peaks corresponding to the fresh and burned gas respectively. The threshold value for discriminating the flame contour is set as the average value between the gray scale of these two peaks.

A high-sensitivity spectrometer *Ocean Optics MAYA PRO 2000* configured with a spectral resolution about 2.5 nm in the range UV-VISIBLE-NIR (200-1100 nm) is used to record flame emission spectra with or without plasma ignition.

3. Results and discussions

Fig. 2. shows two sequences of images of lean methane/air premixed flame for different equivalence ratio without plasma and with plasma. Plasma experiments are conducted with pulse repetition rate at 4 kHz and power supply voltage at 15.2 kV. For the selected equivalence ratios, it is observed that the presence of plasma jet modifies the shape of the flame. The highest modification is for the lowest equivalence ratio for both flow rates. The flame lightness decreases when the equivalence ratio reduces.

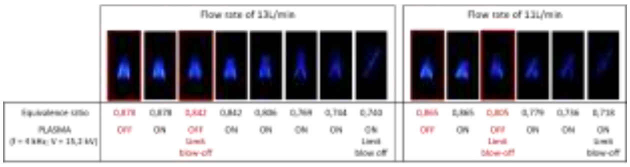

Fig. 2. Sequence of images of the laminar methane-air premixed flame as a function of equivalence ratio with or without plasma (f=4 kHz; V=15.2 kV) for two flow rates.

For a better visualization of the plasma effect, the flame height is plotted in Fig.3. The flame height increases with the equivalence ratio reduction for the two flow rates without or with plasma. For each flow rate, the evolution curves with or without plasma is similar. Moreover, the reduction of the flame height without and with plasma is higher for lower flow rates. The graphic reveals clearly that the methane air premixed flame with plasma is blown-off at lower equivalence ratio than without plasma for both flow rates. Equivalence ratio decreases from 0.842 to 0.74 and from 0.805 to 0.718 for 13 L.min^{-1} and 11 L.min^{-1}, respectively. The plasma effect decreases the flame height for the lowest flow rate i.e. 30% less for 11 L.min^{-1} and 15% less for 13 L.min^{-1}. Also, it reduces the flammability limit at low equivalence ratio for the highest flow rate i.e. 11.2% less for 11 L.min^{-1} and 12.5% less for 13 L.min^{-1}.

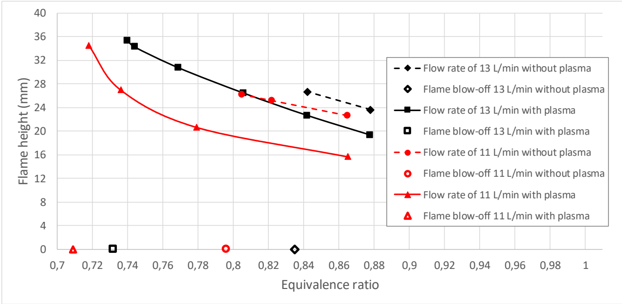

Fig. 3. Height of the laminar methane-air premixed flame as a function of equivalence ratio with or without plasma (f = 4 kHz; V = 15.2 kV) for two flow rates.

The effect of pulse repetition rate is investigated in this study and corresponding sequences of flame images are given in Fig.4. The power supply is tuned with a voltage of 15.2 kV and the equivalence ratio is fixed at 0.865 for 11 L.min^{-1} and at 0.878 for 13 L.min^{-1}. For both flow rates, the generation of plasma induced modifications of the shape and colour of flame mainly for the highest frequencies. The lightning of the flame is stronger and occurs at lower pulse frequency for the lowest flow rate.

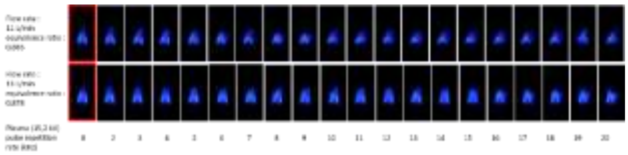

Fig. 4. Sequence of images of the laminar methane-air premixed flame as a function of plasma (V=15.2 kV) pulse repetition rate for two flow rates.

As it is done for the previous sequence of images, the flame height is plotted in Fig.5. as a function of the plasma pulse repetition rate The plasma frequency influences significantly the flame height. It decreases from 24 mm to 16 mm with increasing pulse repetition rate up to 7 kHz and then the flame height stagnates at 16 mm until 20 kHz for a flow rate of 13 L.min^{-1}. this represents a reduction of 33% of the flame height. For the second flow rate (11 L.min^{-1}), flame height decreases from 20 mm to 11 mm with increasing pulse repetition rate up to 8 kHz and then stagnates at 16 mm as in the previous flow rate condition. For this condition, the flame height is reduced by 45 %. Fig.5. illustrates that for low pulse repetition rate the two curves have the same gradient and for high pulse repetition rate the two final flame heights are similar.

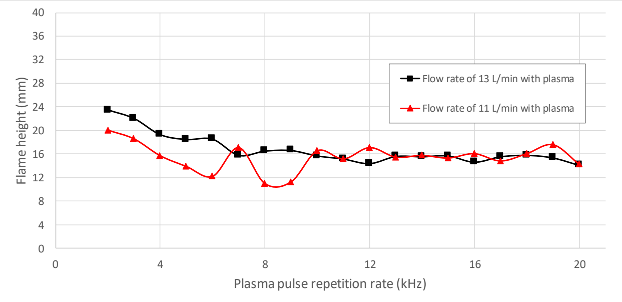

Fig. 5. Height of the laminar methane-air premixed flame as a function of plasma (V=15.2 kV) pulse repetition rate for two flow rates.

Flame emission spectra are recorded without and with plasma at 5 mm above the burner. Two spectra of these experiments are illustrated in Fig.6. These spectra shows that all the species in the flame without plasma are also present in the flame with plasma as OH and CH radicals, except in the range of 330-360 nm corresponding to molecular structure of the second positive system of N_2. These species can induce new reactions at the benefit of combustion processes. More experiments have to be performed to understand better the interaction between the plasma and the methane-air mixture. In addition, it is impossible to conclude on the amount of species because the flame height changes without or with plasma, which involves that spectra cannot be compared.

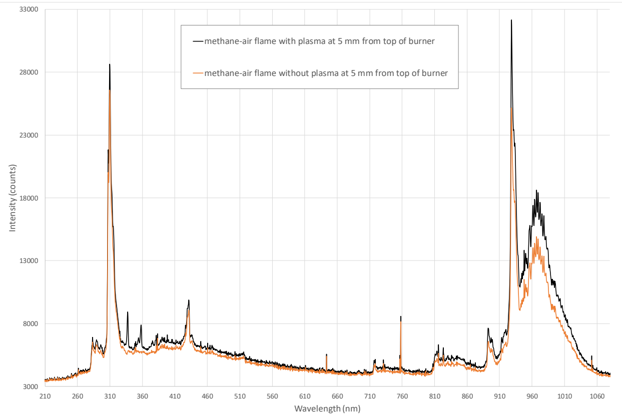

Fig. 6. Spectra of methane-air flame with or without plasma at 5 mm from top burner.

4. Conclusion

An experimental study of an atmospheric pressure plasma jet effects on a lean methane–air premixed laminar flame characteristics is conducted. A plasma gun system is combined with an existing laminar burner. This system operates at low equivalence ratios and does not require any modification of the existing combustion system. Measurements of flame height as a function of equivalence ratio are achieved. The effect of the pulse repetition rate of plasma is also analysed. The results show that the presence of the plasma jet inside the burner upstream the reaction zone improves the flame characteristics. First, the use of plasma in the flame reduces by 15% the highest flow rate and by 30% lowest flow rate. Second, increasing the pulse repetition rate, the flame height decreases by 33% for the highest flow rate and by 45% for lowest flow rate. Third, experiments clearly show that the flammability limit at low equivalence ratio increases by 12 % using plasma. A primary approach based on reactive species produced by plasma can explain in part those observations.

Further investigations are planned shortly in terms of other combustion and plasma parameters (gas flow rates, equivalence ratio, pulse repetition rate, power supply voltage) and optical diagnostics such as spectroscopy and chemiluminescence. This will allow further explanation concerning the plasma jet-combustion interaction.

5. References

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