Pulsed Gliding Arc plasma effects on a CH_4-air turbulent swirling flame

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Abstract: The present paper reports an investigation of the **P**ulsing **G**liding **A**rc plasma (PGA) effects on the CH_4-air combustion. A PGA system is developed and applied to a turbulent flame in a swirl burner. The idea is to combine two techniques of flame stabilization: pulsed gliding arc discharges and a swirling flow to enhance the plasma effect. OH* chemiluminescence measurements are performed to describe the structure and the flame stability. Combustion gases are analyzed as a function of the plasma voltage and frequency.

Keywords: pulsed gliding arc, plasma, combustion, pollutant emissions.

1. Introduction

Combustion control in terms of stability and pollutant emissions is important for optimizing combustion systems. One of the very promising possibilities is the use of plasma source for assistance and support of combustion in lean regimes or in presence of instabilities. Indeed, it is rather flexible technology, low energy consumption, relatively robust and especially requiring only minor structural modifications of combustion devices [1-3]. However, the flame/plasma interaction, in particular using gliding arc, remains an unknown domain and the acting mechanisms are not formally identified. Indeed, the physics of these environments is quite complex. In addition, there are few diagnostics available to characterize the effects of plasma with presence of combustion. Therefore, to date, many questions remain open and require further studies. In this paper, we propose to study the effects of pulsed gliding arc (PGA) on turbulent combustion to help understanding of interaction. The main idea of this project is to create pulsed gliding arc plasma to active control of swirling flame and to estimate the benefits in terms of stability and pollutant emissions. Some studies found in the literature have demonstrated the feasibility and strong influence of gliding arcs on combustion or the opposite [4, 5]. Several studies and projects have been performed on the use of plasma in combustion, in particular with stabilized arcs, such as the use of a dielectric barrier discharge (DBD) [6], or from plasma torch type [1, 7]. However, very few studies are devoted to the effect of gliding arc on combustion. Nevertheless, we can cite some studies done on particular applications, as for examples, the combustion and ignition enhancements of diffusion flames [8], the use of rotating gliding arc reactor for methane oxidation [9], the NOx measurements under gliding arc [10], the interactions between the gliding arc discharge and the premixed flame [11], the flammability limits and hydrogen production [12].

This work reports some results of the pulsed gliding arc plasma effects on the turbulent flame behaviour. A pulsed gliding arc plasma system with adjustable voltage and frequency has been developed especially for this study. Measurements concern OH radicals from combustion zone and pollutant emissions (NOx, CO) on a CH_4-air flame in a swirl burner.

2. Experimental setup

The experimental setup includes the burner, the pulsed gliding arc (PGA) plasma system and measurements techniques. Fig. 1 shows a schematic view of the burner used. The burner has a coaxial configuration with a swirler in the annular part. The air is delivered in the annular part through the swirler to induce the rotation of flow. The swirler is composed by eight vanes with a fixed angle corresponding to the swirl number Sn=1.4. The CH_4 is delivered in the central tube and injected in the combustion chamber through eight small holes. More details about the burner and combustion chamber can be found in the previous works of the authors [13, 14]. The experiments are conducted in a square cross-section chamber of 48×48 cm^2 and 1 m high which is operating at atmospheric pressure. Six windows are placed on each face of the chamber allowing optical access to the entire length of the flame. The walls of the combustion chamber are water cooled on the outside and refractory-lined inside. Experiments are conducted on a turbulent flame with the flow rates of CH_4 and air, which are 150 l/min and 19 l/min, respectively. This corresponds to a flame power of 11.3 kW. The Reynolds number in the annular part, based on D_b=38 mm and the fixed bulk velocity 5.6 m/s is Re=4514.

OH* chemiluminescence measurements are done to describe the structure and stability of the flame. OH* emission is located in the reaction zone where it has been created. This technique throughout OH radicals enables to detect the flame contours and estimate the lift-off heights and the flame length. The experimental setup consists of an ICCD camera (Princeton Instrument PI-MAX Gen II) with a UV Nikkor lens of 105 mm focal length (f / 4.5), a camera control device, an interference filter CG-UG-11-2X2-1.0 (Melles Griot), centred on 306 nm with a bandwidth of 20 nm, and a computer to acquire and save images. Acquisitions of images are done using WinView32 software, which allows recording and viewing images. The camera sensor consists of a size matrix of 1024×1024 pixels² and at output the images are coded on 16 bits. The exposure time is fixed at 40 ms for each image. The real size of images is 112×112 mm^2 with a spatial resolution of 9.2 pixel/mm.

Measurements of combustion products are conducted in flue gases using a HORIBA PG250 multi-gas analyser. This work focuses on NOx and CO emissions. Combustion products are sampled by a PSP4000-HCT sampling probe and transported with a heated transfer line to prevent condensation of water vapor. The sampling probe is located on the central axis of the combustion chamber at 1.2 m from the burner.

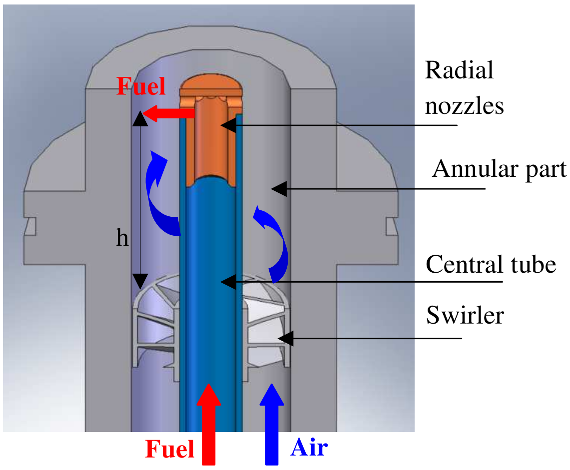

Fig.1. Diagram of the original burner

3. Gliding arc plasma system

Fig. 2 shows the implementation of the plasma system on the burner presented above. This device can create pulsed gliding arcs upstream of the flame or in the flame. The central fuel tube has been lengthened to be used as an electrode for the arc. Two other peripheral electrodes have been positioned symmetrically to treat the maximum of gases. These two electrodes follow the movement of the swirl jet while gradually moving away from the central electrode to ensure the development of the slippery discharge.

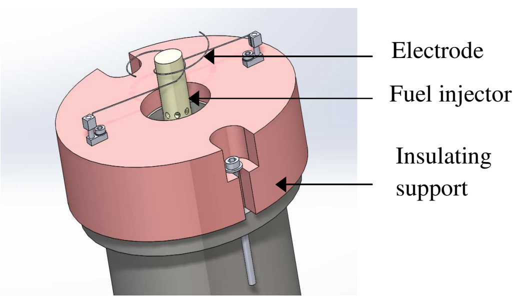

Fig.2. Gliding arc plasma system in the burner

A piece of alumina was added to fix the peripheral electrodes in the combustion chamber and isolate it from the metal burner. Two power supplies have been developed to generate a plasma on each electrode. These pulse power supplies are adjustable in voltage and frequency to change arcs' characteristics. The pulse duration is 1 µs and the frequency is variable from 1 to 20 kHz. The primary voltage is adjustable from 0 to 350 VDC and the secondary voltage from 0 to 20 kV. The maximum instantaneous power thus produced is 150 W at the power output. The maximum instantaneous power supply consumption is 150 W for each power supply. The two frequencies are synchronized to avoid plasma dissymmetry. The original gliding arc discharge (glidarc), first developed by Czernichowski [15], was modified into pulse gliding arc discharge (PGA) to decrease the energy consumption. Thus, two diverging electrodes are placed in the injected rotating gas flow. The discharge forms at the closest point, glides along the electrodes and disappears; another discharge immediately reforms at the initial spot [15]. The plasma create species as for example OH*, CH*, O* which are valuable species for flame stabilization.

Fig. 3 illustrates the presence of the two synchronized pulsed gliding arc plasma at the flame base.

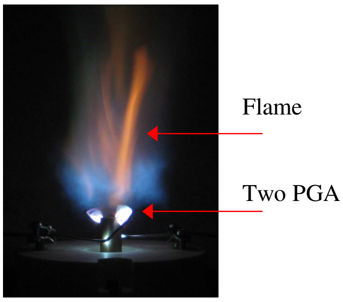

Fig.3. Flame with the pulsed gliding arc plasma (PGA)

4. Results and discussion

Fig. 4 shows a photo of turbulent flame of 11.3 kW in the case without plasma and with plasma. It is observed that the presence of pulsed gliding arc has a effect on the flame. Indeed, the flame weakly changes of the color, shape and behavior. The base of the flame approaches the burner and becomes relatively more stable with the presence of plasma.

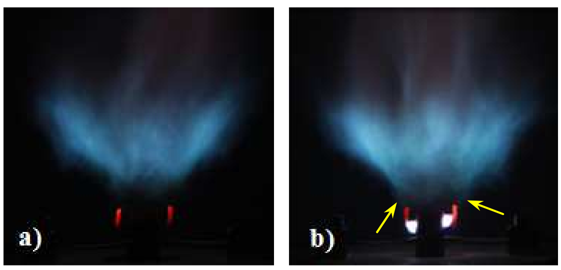

Fig. 4. Photo of flames, a) without PGA, b) with PGA

There are two small branches at the flame base that elongate towards the burner near the two pulsed gliding arcs (yellow arrows on the Fig.4.b). Besides, with plasma, a yellowish zone appears downstream of the reaction zone in the flue gas zone.

Fig. 5 illustrates instantaneous images of OH* chemiluminescence without pulsed gliding arc (left column) and with gliding arc (right column). This case corresponds to 15 kHz of plasma frequency and 100 W of plasma power supply consumption. The average images (Fig.5, line 4) are determined from 200 instantaneous images for each case. The average image is calculated by averaging the light intensity pixel by pixel using a program made by Matlab software. These images clearly show the influence of plasma, especially on the flame base, as was indicated above. Two bonds between flame and plasma, close to the plasma area are clearly visible in the images. These results are very important because of the gain in flame stability.

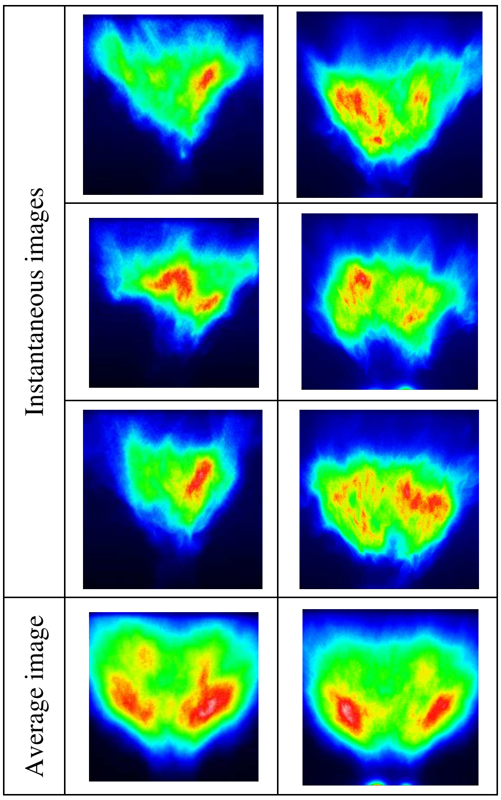

Fig.5. Instantaneous and average Images of OH* chemiluminescence without PGA (on the left), with PGA (on the right) (15 kHz, 100 W).

A Matlab image processing program (thresholding, binarization, filtering and contour detection) is developed to extract lift-off heights (H_{LO}) and flame lengths (L_f).

Fig.6 shows lift-off height of flame and flame length as a function of plasma frequency. Note that the lift-off height is the distance between the burner and the base of flame where the OH* signal appears. The lift-off height of flame increases until 6 kHz then decreases from 6 to 20 kHz. The 15 kHz frequency corresponds to the minimum of H_{LO}, which gives the better stability of flame. Concerning the flame length, it is the opposite, the value decreases until 6 kHz then increases from 6 to 20 kHz. These results are inconclusive and merit further investigation, especially for other flame cases and other plasma parameters such as its intensity.

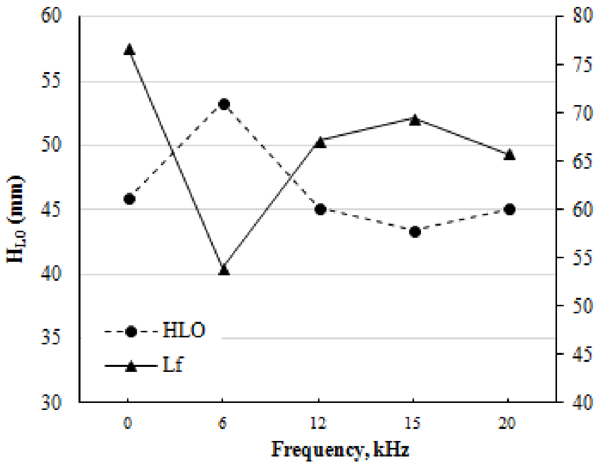

Fig.6. Height of lift-off (H_{LO}) and flame length (L_f) with plasma frequency (power 100 W).

Fig.7 shows NOx and CO emissions with PGA power supply consumption at a frequency of 12 kHz. The effect of PGA power supply consumption is significant on CO emissions and negligible on NOx emissions. Without plasma, the CO rate is 521 ppm. In comparison, with plasma, the CO rate decreases from 211 to 177 ppm between 23 and 120 W. In the case without plasma, the CO rate is 521 ppm. With presence of PGA, even at low power supply consumption (23 W), the decay of CO remain significant. For NOx emissions, the increase from 23 to 120 W does not change the value of 27 ppm. However, without plasma, the NOx rate is 19 ppm. The presence of PGA favors a little the NOx formation and reduces the CO production. This result is often observed in combustion systems, a reduction of CO is accompanied by an increase of NOx and vice versa.

Fig. 8 represents the pollutant emissions (CO and NOx) as a function of the plasma frequency for 40 W of power supply consumption. The PGA frequency influences significantly the pollutant emissions and especially CO reduction. Indeed, the CO rate decreases from 450 to 178 ppm when the frequency shifts from 6 to 15 kHz; it represents a reduction of 60%. For these frequencies, the NOx emissions increases from 20 to 28 ppm; it is an increase of about 28%. It is also noted between the absence of plasma and the low frequency (6 kHz), the NOx increases slightly, from 19 to 20 ppm, while the CO decreases sharply, from 521 to 450 ppm.

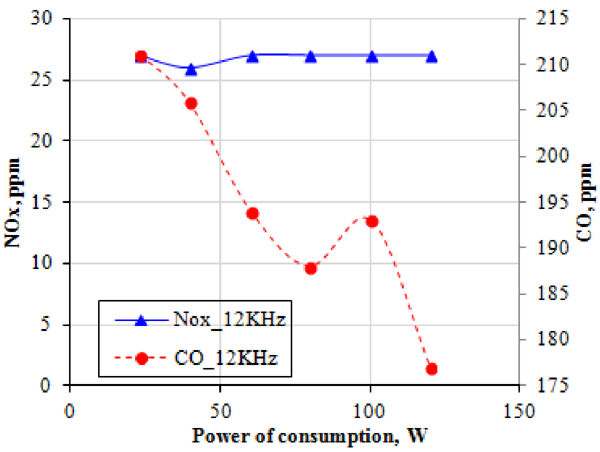

Fig. 7. NOx and CO emissions versus PGA power consumption at 12 kHz

The reduction of CO is a sign that combustion is improving with plasma. This is a priori due to the production of reactive chemical species by PGA which promotes reactions. The increase of NOx is probably related to the increase of local temperature by plasma, which induces NOx formation by the thermal mechanism. Spectroscopic measurements are planned to explain and analyze these results.

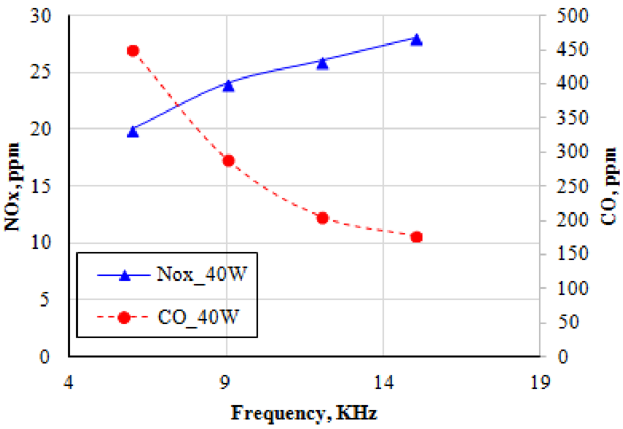

Fig. 8. NOx and CO emissions with PGA frequency

5. Conclusion

An experimental study of pulsed gliding arc plasma effects on CH_4-air swirling flame characteristics is conducted. A synchronized pulsed gliding arc system with double electrodes is developed and placed in an existing burner. This system operates at low power supply consumption (150W max) and does not require any modification of the existing combustion system. Measurements of OH chemiluminescence and pollutant emissions (NOx , CO) on a turbulent flame (11.3 kW) are performed with and without plasma source. The results show that the presence of the PGA improves the flame stability since the flame fluctuates less and clings to the burner. The analysis of combustion products shows a positive impact on CO as its emission rate decreases significantly. However, the results are not convincing concerning NOx emissions because a weak increase of its concentration is observed with the plasma frequency. Further investigations are planned shortly in terms of other combustion parameters (flame power, swirl intensity, equivalence ratio) and optical diagnostics such as spectroscopy. This will allow further understanding of the pulsed gliding arc plasma-combustion interaction.

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7. References

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