Extinction measurements of soot particles in a diffusion flame when submitted to a DC electric field

Pascale Gillon, Virginie Gilard, Mahmoud Idir and Brahim Sarh
ICARE-CNRS, Université d'Orléans
ORLEANS, France

1 Introduction

Pollutant emissions constitute a large drawback of any combustion system and preoccupations to reduce them are constantly animating researches in the combustion domain. Soot particles emitted during combustion and released in atmosphere are identified as harmful for human health [1] but are also known to contribute to the global warming by direct sunlight absorption [2].
The interest to use electric fields in combustion relies on the fact that for a small injected power compared to the combustion power, the potential effects of electric fields on flames are important. The numerous studies devoted to the electric effects on flames have involved multiple configurations: from premixed to diffusion flames, turbulent or laminar submitted to continuous or alternative electric fields with direction opposed, along or transverse to the flame. Motion of charged species in hydrocarbon flames, ions and electrons already present or electrically generated, leads to a large variety of effects when an electric field is applied: either on flame stability (as blow-off limits, flame lift height [3], oscillations [4] as evidenced by the flame current variations), on flame shape [5], increasing the laminar burning velocity as reported in [6-7] for premixed flames and on emissions [8-9]. Saito et al. [8] demonstrated that an applied electric field is able to decrease the total mass of soot generated at the tip of an acetylene flame. In [9], Xie et al.in their investigation of the relationship between luminosity and soot volume fraction of a counter-flow acetylene flame have shown a reduction of soot volume fraction for high frequency and high intensity electric fields.
In addition to the fact that soot presents electric properties, collisions of the accelerated ions with neutrals produce ionic wind able to modify the flow field leading to perturbations in the mechanisms involved in the formation, nucleation and growth, but also in the oxidation of the soot particles. Until now, works have been devoted to small laminar flames with small length limiting the ability to develop sensitive actions on buoyancy convection.
Here we present experimental investigations of a DC electric field influence on the sooting characteristics of a laminar ethylene diffusion flame burning in ambient air, long enough to evidence the effect of electrically perturbed buoyancy convection on soot production. Larger fuel inlet conditions extend the

range of residence times, local stoichiometry, and strain rates, and also open the way to transition to less stable flames and in the gap between laminar and turbulent flames.
Light extinction (LE) is used as the non-intrusive diagnostic technique for measuring soot volume fraction in the configuration of an axisymmetric flame.

2 Experiments

The experimental set-up consisted of a burner and fuel flowmeter, DC power supply and electrode as schematically shown in Figure 1. The fuel was injected through a 10 mm inner diameter nozzle whose length has been designed to insure fully developed velocity profile. Conditions are reported Table 1: the fuel flowrate was of 4 ± 0.1 cm^3/s corresponding to a mean velocity at the nozzle exit of 5 cm/s. The flame issuing from these injected conditions was laminar, stable with a mean length of 80 ± 2 mm. The burner was mounted to a 2D-table to enable it to be positioned within the optical measurement system.

The electric field was generated between the grounded nozzle and a square (105x105 mm2) stainless steel grid (5x5 mm mesh) electrode positioned 140 mm above the nozzle exit. A positive voltage was applied to the electrode using a DC power supply with maximum voltage of 20 kV.

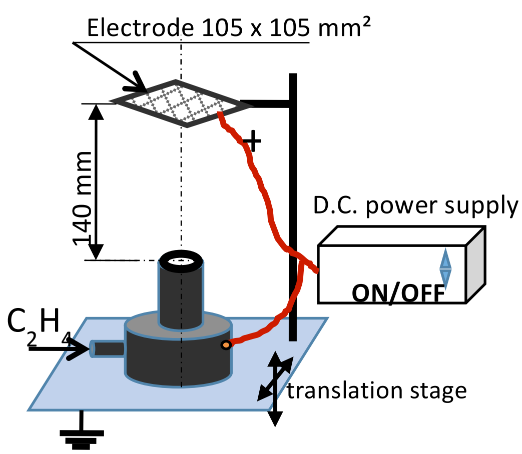

Figure 1. Experimental set-up

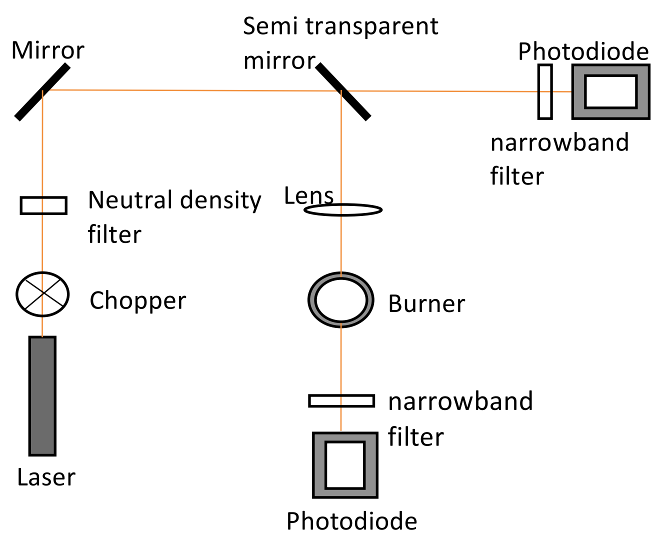

Figure 2. Optical arrangement

Table 1: Experimental conditions

fuel	Flow rate (cm^3/s)	Velocity (m/s)	Flame length (mm)
C_2H_4	4	0.051	80

The laser extinction measurements were performed using a 5 mW DC He–Ne laser at 632.8 nm wavelength as shown in Figure 2. The laser beam was splitted in two using a beamsplitter in order to measure the reference (on photodiode 1) and the extinction signal through the flame (on photodiode 2).

The laser beam is focused into the flame using a biconvex lens with a 300 mm focal length. Considering a Gaussian beam, the beam waist at the center of the flame was about 240 µm. An interferential filter, centered at 632.8 nm ± 1 nm FWHM was installed in front of each detector. The sensitive area of the detectors was large enough (3.5x3.5 mm²) to neglect the influence of beam deflection. A neutral density filter was mounted before the beamsplitter in order to avoid any saturation of the detectors.

The contribution of the flame emission on the measured extinction was taken into account through the use of a mechanical chopper modulating the laser beam at 200 Hz.

The line-of-sight absolute value of soot volume fraction was calculated using the following equation

$$fv = -\frac{\mathrm{Ln}(\mathrm{I}/I_0).\lambda}{6\pi.E(m).L} \tag{1}$$

with fv the mean soot volume fraction averaged along the line-of-sight, I and I_0 the intensities of the extinguished and the reference beams, respectively, λ the laser wavelength, E (m) a function of the refractive index of the soot and L the laser path length through the flame. The value of E (m) = 0.26 is chosen based on [10]. Value of L at each height has been deduced from flame images. Error bar on fv is estimated between 4 and 8% due to uncertainties on L measurements especially at the flame tip.

3 Results and discussion

The electric field distribution was calculated using a FEMM software in order to determine the conditions for which the field between the burner and the electrode is uniform for the case without flame. The result obtained for a voltage of 10 kV is shown in Figure 3. The simulation revealed that a quasi-uniform electric field can be generated when a large electrode is used with a gap of 140 mm. For the previous conditions, uniformity of the field was calculated to be within 10% over the central 80 mm of the flame.

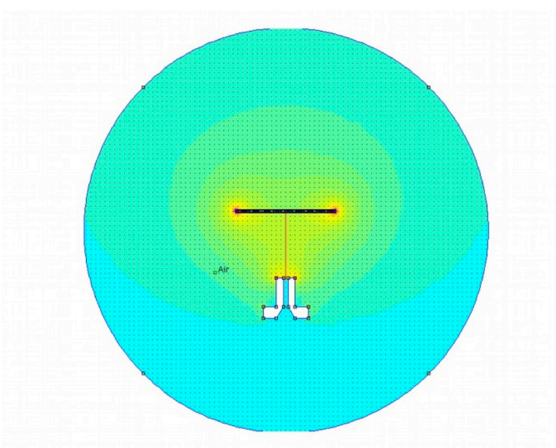

Figure 3. Calculated electric field +10 kV on electrode and 140 mm gap without flame

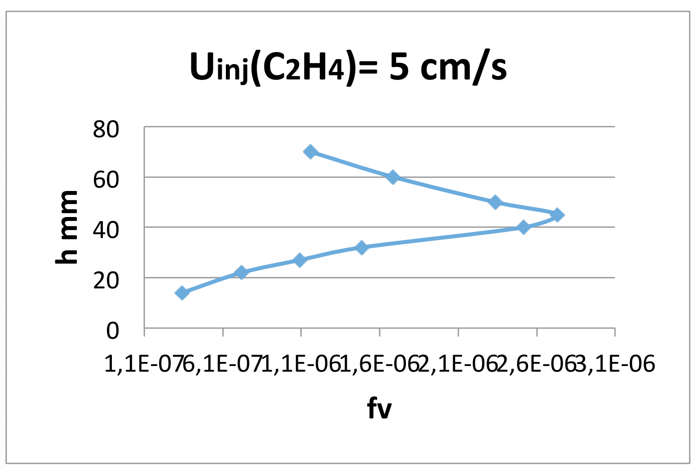

Figure 4. Mean soot volume fraction on the flame axis 0 kV

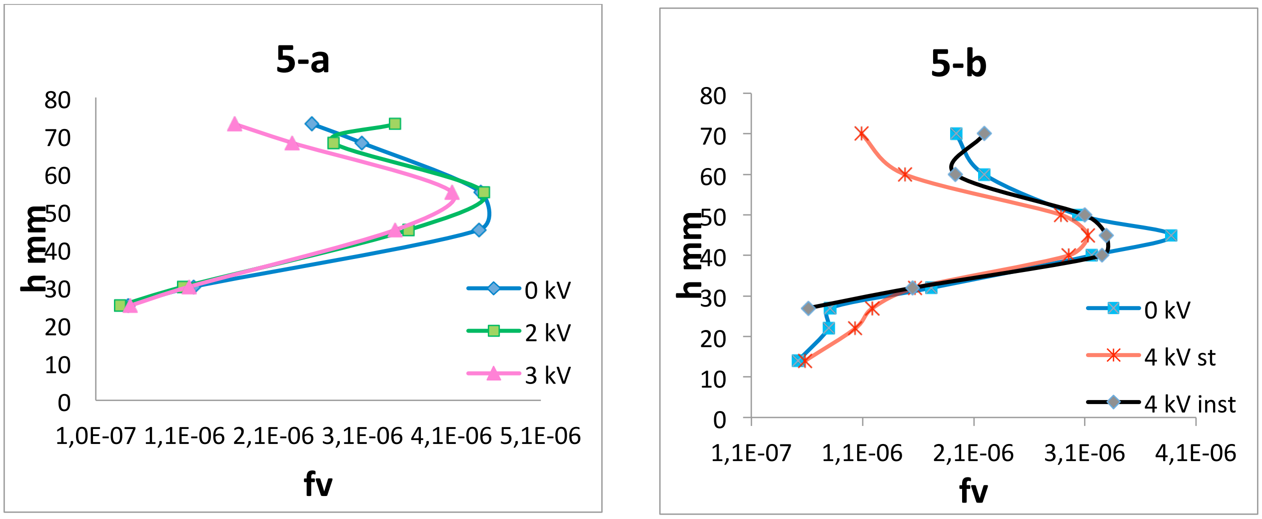

Figure 5. Variation of the soot volume fraction along the flame axis with the voltage intensity: a-stable flames b-comparison between stable and unstable flames

The extinction measurements were performed axially at heights above the burner (HAB) from 14 mm to 70 mm. Figure 4 reports the data of mean soot volume fraction on the flame axis when no electric field is applied. The concentration of particles low at the flame bottom reaches a maximum at about 45 mm HAB and then decreases in direction of the flame tip. This variation illustrates the steps of formation, agglomeration and oxidation of soot. Results are comparable with the ones obtained by Santoro et al. [11] validating the LE diagnostic method. Influence of electric field is reported Figure 5. Measurements have been performed at low values of voltage of 2 and 3 kV (Figure 5-a), where the flame electrical current is supposed sub-saturated. In the sub-saturated regime, flame shape and stability are preserved allowing comparison with data obtained at 0 kV. The soot volume fraction is systematically reduced when a downward electric field is applied to the flame. In this configuration of an electric field directed toward the burner surface, positive ions are driven downwards. As the ionic wind generated through collisions of ions with neutrals is predominately due to the positive ions, the upward fluid motion due to inlet inertia is counteracted by a downward electric contribution toward the burner. Consequently, the gas flow is slowed down essentially at the flame front where ions are concentrated due to the combustion reaction. The shear flow along the flame front has multiple consequences: first a modification of the convective flow as ionic wind counteracts buoyancy, a modification of the reactant mixing limiting the oxygen transport to the front associated to chemical perturbations and a longer residence time for the particle in formation. These complex coupled effects could be responsible for the observed decrease in the soot volume fraction consistent to what has been observed by Saito et al. on an acetylene flame [8].

Higher voltage values causes onset of flame instabilities. At 4 kV the ethylene flames are characterized by periodic oscillations of flame length at low frequency similar to the flickering phenomena. Measurements of time averaged soot particles concentration for an applied voltage of 4 kV are reported in Figure 5b in the cases of stable and unstable flames. Flame oscillations triggered and sustained by the applied 4 kV are shown to increase the mean particle concentration measured on the flame axis. Results are coherent with the cases studied by Shaddix et al. [13] in the case of sonic triggered flickering flames. Onset of flickering instability observed as an increasing voltage is applied could be related [4] to the behavior of the flame current variation when the flame current transitions from the sub-saturated current regime.

4 Conclusion

By using a common laser extinction diagnostic technique, demonstration of the influence of a DC electric field has been shown on the formation of soot particles in ethylene diffusion flames. The particle distribution on the flame axis low at flame base and tip and maximum at the mid flame height seems not modified by the electric field. However, the soot particle mass volume fraction is systematically found lower in stable flames submitted to a continuous electric field. This beneficial electric effect is lost when the flame becomes unstable at higher voltages. Oscillations of the flame length triggered by the electric field contribute to increase the soot particle mean concentration measured on flame axis. Considering that the electrical effect on buoyancy convection is supposed to concentrate in the shear layer along the rich part of the flame front, detailed measurements of the soot particle concentration versus the flame diameter at different flame heights is under way.

References

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