Characterization of soot in a co-annular ethylene diffusion flame when submitted to a dc electric field.

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1 Introduction

Combustion-generated soot which have a significant impact on climate change and human health is dependent on its size and morphology [1,2]. That's why a large part of research in the combustion domain has been dedicated to soot formation and reduction processes. Application of electric fields during combustion has shown a potential effect in reducing soot production [3]; it has been studied for many years and the ionic wind constitutes the main explanation of the observed effects on the flame structure and pollutant emissions. The interaction mechanisms of an electric field with a diffusion flame involve both ionic wind and direct action on charged particles. Here, the effects of a dc electric field on the soot characteristics of a laminar 65 mm-long ethylene diffusion flame burning in an air co-flow are investigated.

2 Experiments

The co-annular burner used in this study is composed of two co axial tubes: a 7.8 mm diameter inner fuel tube and and an outer 40 mm inner diameter air tube forming the external burner body. The burner was mounted on a 2-axis (transversal and vertical) translation table. Ethylene was used as fuel (purity > 99.95%). It was injected with a constant flow rate of 3.1cm^3.s^{-1} corresponding to a mean velocity of 6.5 cm.s^{-1} at the nozzle exit. The air co-flow was injected with a constant velocity of 6.1 m.s^{-1}. Under these conditions, a low Reynolds number is reached, and a non-sooting stable laminar diffusion flame is developed with a flame length of 65 mm without applying electric field.
A square (105 mmx105 mm) stainless steel meshing grid electrode was placed 140 mm above the burner. It is consisted from 15x15 wires (1 mm of diameter) forming a square meshing grid in order to evacuate the burned gas without introducing major perturbations to the electric field and to limit the flow resistance.

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The positive potential was connected to the burner while the downstream electrode was grounded. Therefore, an electric field directed from the burner to the electrode referred as positive direction was generated. A positive voltage of 8 kV was delivered by a dc power supply giving an electric field strength of 0.57 kV/cm.

Laser Scattering/Extinction technique has been used to characterize the soot particles in the flame. Figure 1 displays a schematic of the optical setup to measure simultaneously light scattering and extinction point to point in the flame. A 5 mW DC He-Ne laser, at λ_e = 632.8 nm, was used for extinction measurements and a 300 mW, λ_s = 532 nm, DC Nd:YAG laser (Laser Quantum, Opus) was used for laser scattering measurements. The mechanical chopper (200 Hz frequency) was aimed to differentiate between the flame emission and the collected laser signals. A neutral density filter (ND = 2) was settled in the red laser path to avoid any saturation and to ensure a linear response of the detectors. The He-Ne beam was divided in two segments with the aid of beam splitter. The first one was used as the reference beam. Its intensity was measured by photodiode 1. The second was focused in the flame with a 150 mm focusing lens. The transmitted intensity through the flame was measured by photodiode 2. A 632.8 nm laser line filter with 3 nm bandpass was mounted in front of each photodiode. The red and green laser beams are superimposed by the mean of a dichroic mirror. For scattering measurements the green scattered beam from the focal volume was collected at 90 ° relative to laser beam axis. This scattered light was collected with the help of 150 mm and detected and measured by a photomultiplier tube (Hamamatsu, R928). A 1 mm diameter pinhole was installed at the image position of the probe volume, in order to identify the probe volume, and then the spatial resolution of the measurements. A 532 nm laser line filter, 1 nm bandwidth, and, a ND = 3.0 neutral density filter were mounted in front of the photomultiplier. In order to increase the signal to noise ratio of the scattering measurements, a 300 mm radius of curvature concave spherical mirror was installed at the opposite of the PMT. The transmitted green laser beam is reflected by a dichroic mirror and confined into a laser trap in order to avoid any supplementary signal detection by photodiode 2.

At 632.8 nm, the soot volume fraction was calculated using equation (1):

$$\mathrm{f_v} = \frac{K_e.\lambda_e}{6\pi.E(m_{\lambda_e})} \tag{1}$$

Where K_e is the extinction coefficient, calculated using Beer-Lambert law and by applying Abel's inversion, λ_e is the extinction wavelength and $E(m_{\lambda_e})$ is a function of the refractive index at λ_e ($E\left(m_{\lambda_e}\right) = 0.23$).

Under Rayleigh's limit of the Mie's theory (*λ/d>10*), the sixth to third moment ratio, the number of concentration, and the particle diameter can be related to the measured values of the scattering coefficient at 90° and the extinction coefficient as expressed in equations (2-3) [2]:

$$D_{63} = \left(\frac{\lambda_s^4}{\lambda_e}\right)^{1/3} . \left[\frac{4}{\pi^2} . \frac{E\left(m_{\lambda_e}\right)}{F\left(m_{\lambda_s}\right)} . \frac{K_s^{90°}}{K_e}\right]^{1/3} \tag{2}$$

$$N = \frac{12 f_v}{\pi D_{63}^3} \tag{3}$$

With D_{63} is the sixth to third moment ratio, λ_s is the scattering wavelength, $F\left(m_{\lambda_s}\right)$ is a function of the refractive index of soot at λ_s ($F\left(m_{\lambda_s}\right) = 0.52$), $K_s^{90°}$is the scattering coefficient at 90° and N is the soot number concentration. The values of functions $E(m_{\lambda_e})$ and $F\left(m_{\lambda_s}\right)$ are referred to [4].

The transmittance was measured as function of r, the distance from flame axis (equation 4):

$$T(r) = -\ln\left(\frac{I}{I_0}\right) \tag{4}$$

Here, T is the transmittance, I the intensity of the transmitted light beam (measured by photodiode 1) and I_0 the intensity of the incident one (measured by photodiode 2). The radial distribution of the extinction coefficient K_e was obtained by Abel inversion. The measured data were spline interpolated and then de-convoluted by the means of a three point method [5].
Each measurement is the average value of 60 readings obtained over a period of 2 minutes.

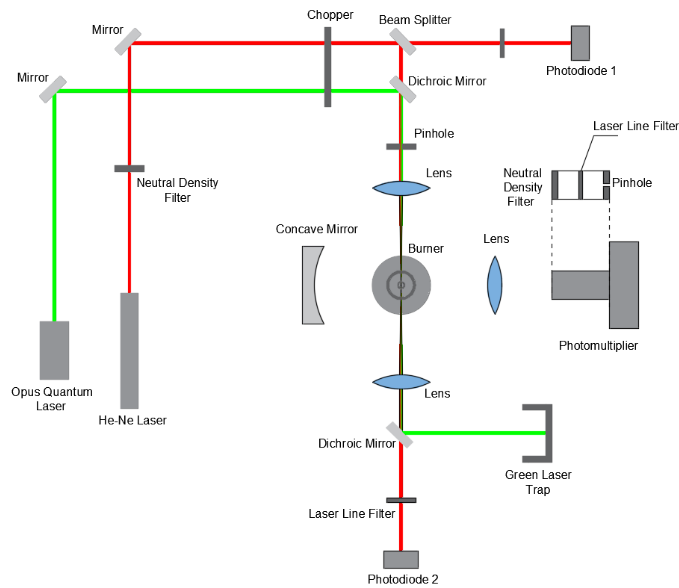

Figure 1. Schematic of the optical setup

3 Results

The flame shape is modified when submitted to the electric field. The flame remains stable but appears larger and shorter. Initially of 65 mm long without electric field, the flame length attains 58 mm under 8 kV. The lateral extension of the flame could be explained by the increased burning rate as observed by Won et al. [6]. It could also be related to the modification of the flow field by the ionic wind effect which may provide a better mixing of fuel and air. Figure 2 presents the variation of the soot volume fraction, the particle diameter and the soot density number along the flame radius for 3 values of height above burner (HAB): 19.5, 29.5 and 39 mm at a voltage of 0 and +8 kV applied to the burner. The validity of the optical measurements without electric field has been assessed by comparing with the results obtained by R.J. Santoro et al. [7]. As already observed [7] the soot being negligible at the flame center, develops first near the flame edge and progressively expands toward the flame axis until oxidation causes a decrease of soot concentration.
Results of soot volume fraction, mean particle diameter D_{63} and particle number concentration are plotted versus the radial position in the flame at three values of HAB in Figure 2. It shows that the application of an electric field has a strong influence on the soot production in the flame.

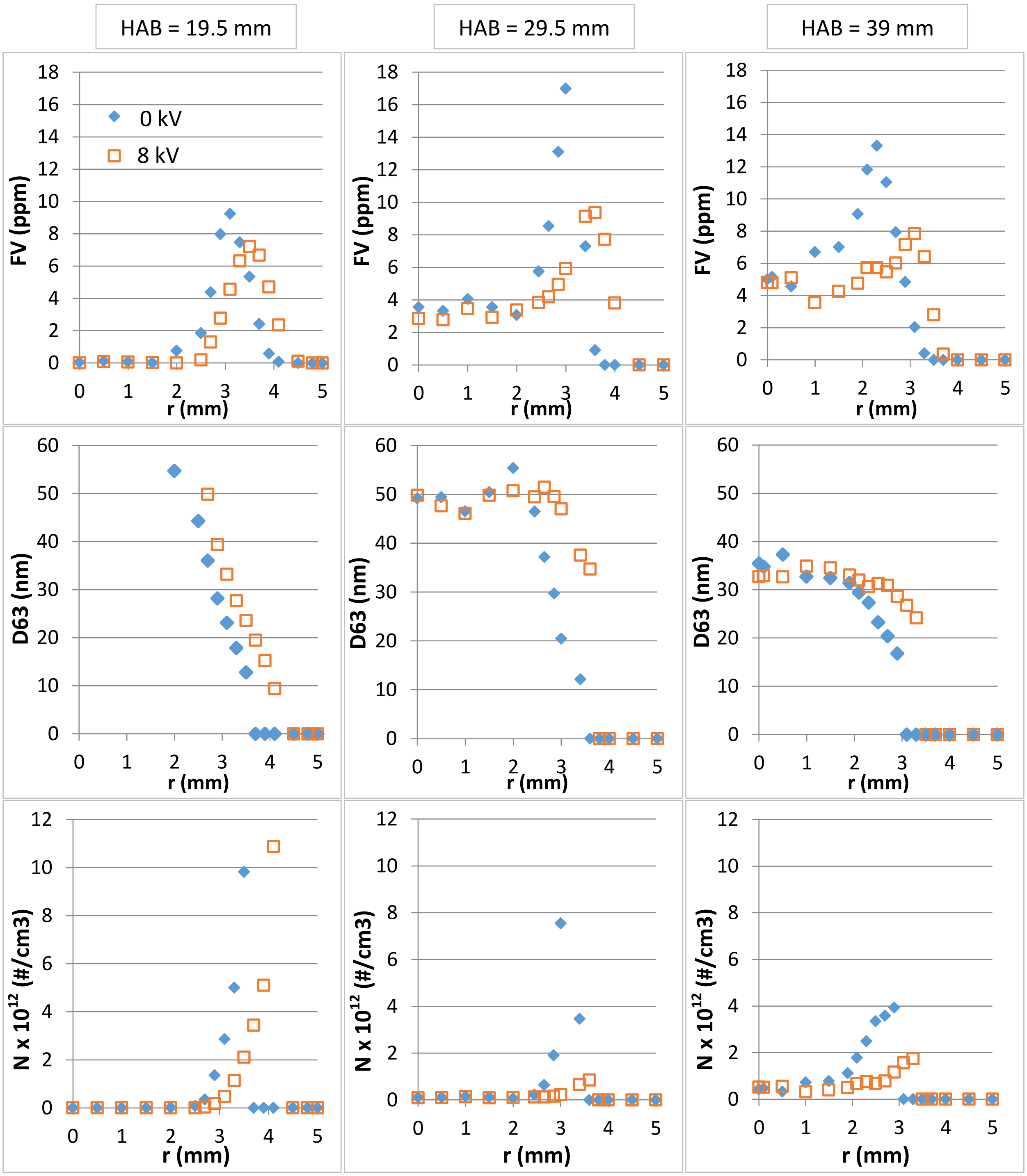

Figure 2. Soot volume fraction fv, particle mean diameter D_{63} and number concentration N along the flame radius at 19.5, 29.5 and 39 mm HAB positions.

A remarkable effect of the electric field is the decrease of soot volume fraction for all the investigated positions in the flame. It confirms the effects of electric field on soot production that have been observed previously only on the flame axis [8].
The radial evolution of the soot volume fraction obtained without electric field is in agreement with the one described in the literature [9]. At HAB=19.5 mm, in the low region of the flame, soot particle inception is prominent in an annular region with very few particles reported in the central region. Radial variation of f_v at HAB=29.5 and 39 mm show a similar shift of the peak in the annular region and a progressive increase of particle detection toward the flame axis for the upstream position.
When the voltage of 8 kV is applied, the radial variation of the soot volume fraction presents a curve similar to the one without electric field but with smaller values at each point of measurement in the flame. It is observed that the modification of the flame shape leads to an external shift of the position of the soot volume fraction peak coincidently with the observed increase of the flame diameter. The reduction of the flame length seems to accelerate the soot oxidation as less soot is measured in the annular region for HAB=39.
Particle number concentration and mean particle diameter measurements confirm this tendency: a lot of particles are concentrated in the annular part in the low region of the flame in the vicinity of the flame front and less and less particles in the annular region when going upstream. Particle diameter is observed to decrease when progressing upstream in the flame. When the electric field is applied, particles show a larger mean diameter and a lower number concentration. This effect could suggest that the growth mechanism of particle by agglomeration of primary particles is promoted by the electric field.

4 Conclusion

The non-intrusive Scattering/Extinction method has been implemented to investigate the effect of a dc electric field on soot volume fraction and particles diameter formed during combustion in a co-annular diffusion flame of ethylene. Interestingly, when a positive potential is applied at the burner, the flame exhibited a reduction in flame height and an increase in diameter. This fact has been attributed to the ionic wind modifications affecting the internal dynamic of gases, especially near the burner nozzle. The measurements of soot volume fraction, particles mean diameter and particle number concentration were taken at different HAB with 8 kV of potential applied at the burner. A reduction in soot volume fraction and number of concentration of particles was observed under the effect of the electric field while the particle mean diameter was bigger. This result is mainly due to the modification in residence time and in temperature generated by ionic wind in the flame that has a strong influence on the particle formation, growth and oxidation. A specific effect of electric interaction between charged species in the mechanism of agglomeration could be considered to explain the increase of the mean particle diameter in the vicinity of the flame front. Further investigations involving a multi angle scattering set-up are under development to confirm this specific effect.

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