Sliding Discharge Optical Emission Characteristics

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ABSTRACT

In this work, several optical studies in an atmospheric pressure sliding plasma sheet have been performed. This discharge is generated using two electrodes flush mounted on an insulating flat plate (upper electrodes), and a third electrode flush placed on the opposite side of the plate facing the upper inter electrode gap (lower electrode). A dc negative voltage is applied to one of the two upper electrodes and to the lower electrode, while the other upper electrode is biased with an ac voltage. In this configuration a sliding discharge is produced on the flat plate within the upper electrode's gap. The sliding discharge optical emission of the spectral bands corresponding to the 0-0 transition of the second positive system of N_2 (λ = 337.1 nm) and the first negative system of N_2^+ (λ = 391.4 nm) have been measured. Also the light spatial distribution in the plasma sheet has been studied using a CCD camera coupled to interferential filters corresponding to the wavelengths investigated. The reduced electric field in the plasma sheet has been derived from the measurement of the intensity ratio of the Nitrogen lines. This study has been realized varying the amplitude of the dc voltage and the amplitude and frequency of the ac voltage. The reduced electric field strength is found to be almost constant for all the experimental conditions, with a value of 500 ± 100 Td (1 Td = 1.10^{-17} V cm^2).

Index Terms — **Surface discharges, sliding discharge, plasma devices.**

1 INTRODUCTION

THERE is a remarkable interest in developing low-power non-thermal plasmas at high pressure. Their main advantage is that a non-equilibrium plasma state in atmospheric pressure gases can be established in an economical and reliable way. This plasma is characterized by a low ionization degree, so the electric energy delivered by the external power supply goes into the heating of a few numbers of electrons, while the heavy particles (ions and molecules) remain relatively cold. Up to now, non-equilibrium plasma discharges have been employed in several applications, including ozone production, surface modification of polymers, excitation of CO_2 lasers,

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pollution control, and more recently plasma display panels for flat television screens (see [1] and references there in). Although most of these applications involve volume discharges, surface discharges have been also employed as ultraviolet sources for lasers (see [2] and references there in). Surface discharges are also being actively investigated in aerodynamic applications, that is, the control of the boundary layer of aerodynamic moving objects by using the "electric wind" they produce, or by a modification of some physical properties of the gas (viscosity, density) at the vicinities of the surface [3].

Despite numerous advances in applications of surface discharges to practical devices, many of the basic physical processes are not well understood. This is likely due to the use of different power sources (dc, ac or pulsed), different electrodes geometries, and different gas pressures and gas mixtures, that lead to a large variety of discharge modes (including filamentary, regularly patterned or diffuse discharges [4]).

In this work, optical emission features of an atmospheric pressure surface discharge in air generated by the combined action of dc and ac power supplies applied over three electrodes have been investigated. This kind of discharge is known as a sliding discharge (SD). The SD has been developed in a joint effort between the groups of the Universities of Buenos Aires and Poitiers. The electrode configuration was developed following a previous work dedicated to the study of pulsed discharges in the framework of laser research [5]. The main features of the SD are that it is easy to turn on and to be sustained for large time periods, and also it can cover up large areas of insulator material with a dense filamentary structure. These characteristics make it an interesting candidate for boundary layer control of moving object, among others applications. Several electric and fluid-dynamics techniques were employed to study the sliding discharge [6-9].

In this work we present a spectroscopic study of the most relevant visible emission lines of the discharge, that allow to infer the value of the reduced electric field in the plasma sheet for several values of the discharge electrical parameters. Also, the light spatial distribution in the plasma sheet has been studied using a CCD camera coupled to interferential filters corresponding to the wavelengths investigated. It is found that the electric field results almost independent of the values of the electrical parameters of the discharge, and corresponds to the reported values at a streamer tip.

It is then concluded that the discharge presents a dense filamentary structure composed of cathode-directed streamers almost evenly distributed over the electrodes side length.

2 EXPERIMENTAL SET-UP

The SD was generated using two electrodes (named 1 and 3) flush mounted on an insulating flat plate, and a third electrode (named 2) flush placed on the opposite side of the plate facing the upper inter electrode gap. A dc FUG power supply (35 kV, 4 mA) biased negatively electrodes 2 and 3 (V_{DC}), and a function generator coupled to a TRECK amplifier (400 mA, 20 kHz) supplied an ac sine voltage (peak to peak value from 0 to 20 kV) to electrode 1 (V_{AC}). The flat plate was made of poly-methyl methacrylate (PMMA) with a thickness of 4 mm. The electrodes were made of aluminum bands of 50 µm thickness with a length of 150 mm and a wide of 40 mm (1 and 3), and 30 mm (2). In this configuration the SD was produced on the flat plate within the upper electrode's gap (that is, between electrodes 1 and 3).

The electrode arrangement was placed inside an environmental chamber.

The chamber was a PMMA hollow cylinder with two end plates, the height of the chamber was 130 mm, the radius 350 mm and the wall thickness 6 mm.

The chamber gas (dry air) was removed at the end of each experiment through a vacuum pump and during the experiment a small gas flow assured a relatively constant composition of the gas inside the chamber. Although special care was taken during the pumping or filling of the chamber, no measurements of gas composition were performed in this work.

First, a dielectric barrier discharge (DBD) was established by increasing the amplitude and frequency of V_{AC}. Then V_{DC} was turned on and increased until the SD appeared at the inter electrode space on the upper side of the plate. The dc voltage was varied between –14 kV to –20 kV. The ac voltage was varied between 13 kV and 20 kV (peak to peak), while its frequency (f) was varied between 3 and 11 kHz. Note that within the quoted range of voltage values, electrodes 2 and 3 were always negative with respect to electrode 1.

In order to collect the light emitted from the SD, a system of two collimating lens was employed. The focus was adjusted in order to place the system focal plane in a central section of the upper electrode's gap (see Figure 1). The field of view of the optical system was a circle of 10 mm diameter.

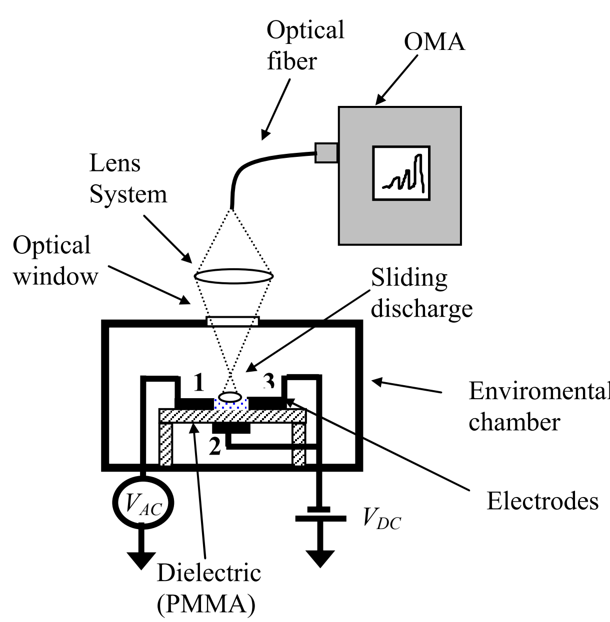

Figure 1. Experimental set-up.

The light emitted from the SD passed through an optical window located at the upper cover of the environmental chamber and through the lens system and focused at the entrance of a quartz optical fiber coupled to the entrance slit of a monochromator. For the study of the spectral bands, the monochromator employed was a SOPRA F1500 of the Ebert-Fastie-type with a focal length of 1500 mm and a diffraction grating of 1800 grooves/mm. The detector was an intensified OMA (Princeton Instruments IRY 1024). The intensities of the spectral bands corresponding to the 0-0 transition of the second positive system (SPS) of neutral nitrogen molecule N_2 (band head wavelength λ = 337.1 nm) and the first negative system (FNS) of ionized molecule N_2^+ (band head wavelength λ = 391.4 nm) were experimentally determined varying the amplitude of V_{DC} and the amplitude and frequency of V_{AC}. The ratio of the intensities of FNS and SPS band head was used to determine the average value of the reduced electric field θ (being the reduced electric field $\theta = E/N$, with E the absolute electric field and N the total number density of air molecules) [10-12].

Optical images of the plasma sheet were obtained using a CCD camera coupled to interferential filters corresponding to the FNS and SPS wavelengths. A CCD Princeton PI-MAX camera coupled to 337 and 391 nm interferential filters was employed to image the discharge at a wavelength corresponding to intense emission from the excited species present in the plasma. The camera was focused in such a way that both electrodes edges and the inter-electrode gap were within the picture frame.

A scheme of the experimental set up is shown in Figure 1.

3 Experimental Results

A typical overall emission spectrum of the SD is presented in Figure 2. No relevant emission lines were found in the wavelength range 490 – 800 nm. It can be seen that the relevant lines correspond to N_2 and N_2^+ (much weaker) vibrational transitions.

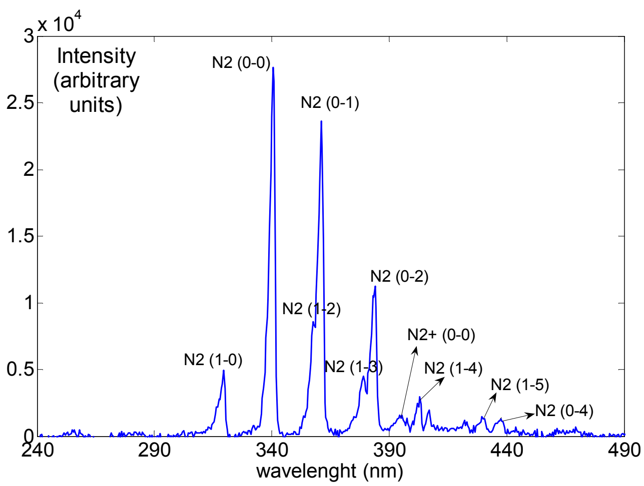

Figure 2. Typical molecular spectra of the sliding discharge in air (V_{DC} = -14.5 kV, V_{AC} = 19 kV, f = 7 kHz).

Typical detailed spectra corresponding to the FNS and to the SPS molecular Nitrogen systems are presented in Figure 3. The acquisition time of the OMA was 2 s.

For each band, the intensity as a function of V_{AC}, V_{DC} and f was measured. This intensity corresponds to the maximum of the vibrational band head (0-0). It should be noted that wavelength differences in the sensibility of the optical system were taken into account by normalizing the detector count number to the SPS line (in practice, this meant that the count number corresponding to the FNS line was reduced by a factor of 8).

In Figures 4 and 5 the intensity as a function of V_{AC} for f = 7 kHz and V_{DC} = -14.5 kV for both spectral lines are presented. It can be seen that in both cases the intensity increases smoothly with V_{AC}.

In Figures 6 and 7 the intensities for both spectral lines as a function of $-V_{DC}$ for V_{AC} =15 kV and f = 7 kHz, are presented.

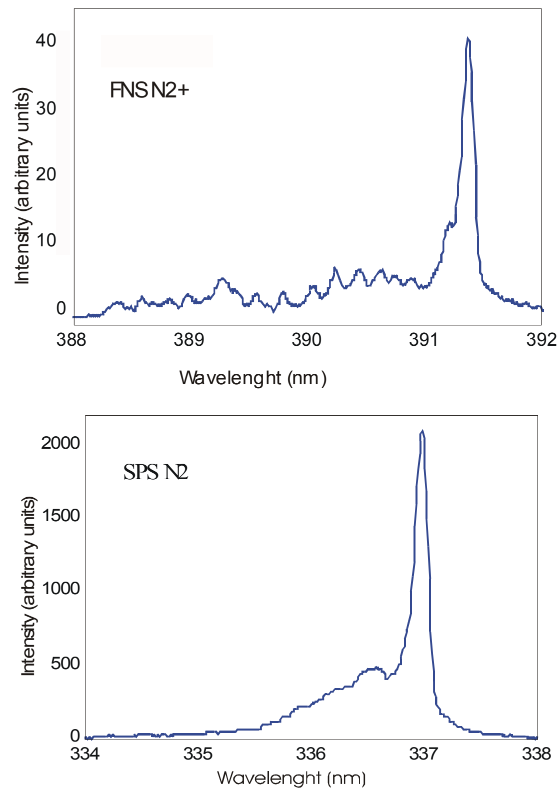

Figure 3. Typical molecular Nitrogen spectra for an air sliding discharge.

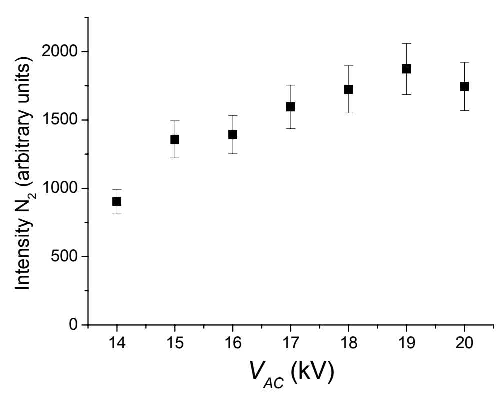

Figure 4: SPS intensity vs. V_{AC} for f = 7 kHz and V_{DC} = -14.5 kV.

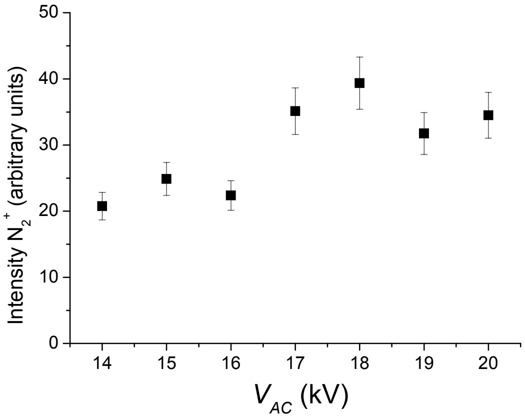

Figure 5. FNS intensity vs. V_{AC} for f = 7 kHz and V_{DC} = -14.5 kV.

From Figures 6 and 7 it can be noted that the intensity remains approximately constant within the whole range of V_{DC} values.

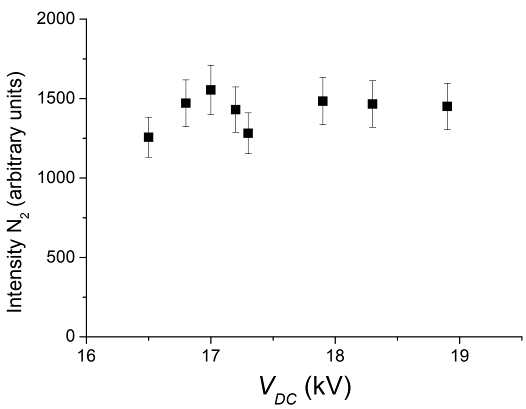

Figure 6. SPS intensity vs. -V_{DC} for V_{AC} =15 kV and f = 7 kHz.

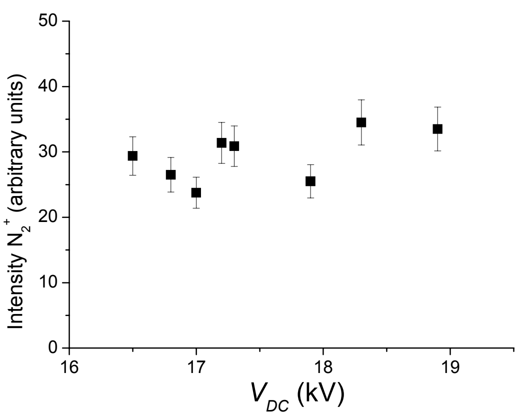

Figure 7. FNS intensity vs. -V_{DC} for V_{AC} =15 kV and f = 7 kHz.

Also, intensity measurements of the lines were performed varying the AC voltage frequency in the range of 3 - 11 kHz. In this case, the line intensities remained also almost constant for the whole range of investigated frequencies.

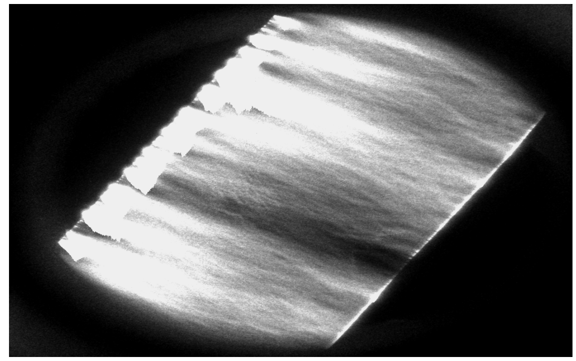

Figure 8. CCD image for an air sliding discharge without interferential filters (V_{DC} = -14.5 kV, V_{AC} = 15 kV, f = 7 kHz).

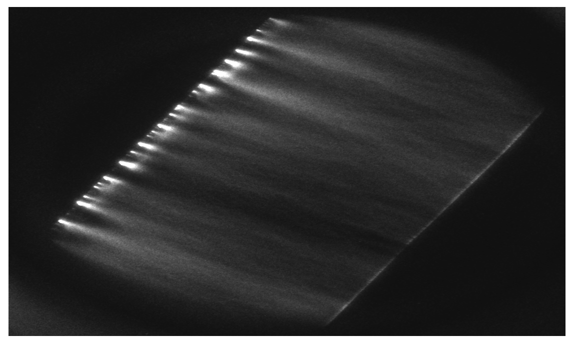

Figure 9. CCD image for an air sliding discharge filtered with a 337 nm interferential filter (V_{DC} = -14.5 kV, V_{AC} = 15 kV, f = 7 kHz).

From the images obtained with the CCD camera without interferential filter, it can be seen that the SD consists in diverging plume of several filaments with its vertex on the anode, almost filling the discharge gap (Figures 8, 9 and 10). The CCD images confirmed what it was observed in the spectroscopic measurements: the SPS intensity (Figure 9) was higher than the FNS intensity (Figure 10), and for both lines the intensity was higher near the electrode 1 where the DBD discharge is initiated.

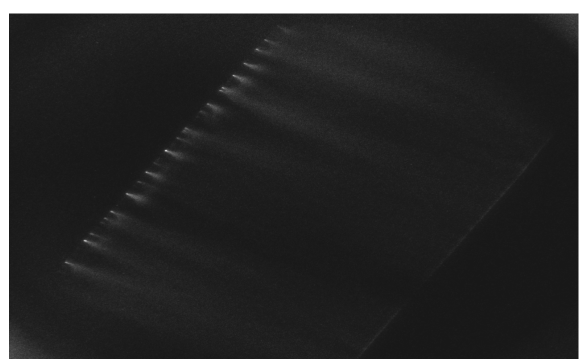

Figure 10: CCD image for an air sliding discharge filtered with a 391 nm inferential filter (V_{DC} = -14.5 kV, V_{AC} = 15 kV, f = 7 kHz).

4 ANALYSIS OF THE EXPERIMENTAL DATA

According to [13], the origin of the light emission from the SD is the process:

$$\begin{aligned}
& e + N_2\left(X^1\Sigma_g^+\right)_{v=0} \rightarrow N_2\left(C^3\Pi_u\right)_{v'=0} + e \\
& \Delta E = 11 eV \\
& N_2\left(C^3\Pi_u\right)_{v'=0} \rightarrow N_2\left(B^3\Pi_u\right)_{v''=0} + h\nu \\
& \lambda = 337.1\, nm, \quad \tau = 40\, ns
\end{aligned} \tag{1}$$

for the SPS spectral band head (0,0), and

$$\begin{aligned}
& e + N_2\left(X^1\Sigma_g^+\right)_{v=0} \rightarrow N_2^+\left(B^2\Sigma_u^+\right)_{v'=0} + 2e \\
& \Delta E = 18.7\, eV \\
& N_2^+\left(B^2\Sigma_u^+\right)_{v'=0} \rightarrow N^+{}_2\left(X^2\Sigma_u^+\right)_{v''=0} + h\nu \\
& \lambda = 391.5\, nm, \quad \tau = 60\, ns
\end{aligned} \tag{2}$$

for the FNS spectral band head (0,0).

In air at atmospheric pressure, the excitation process only comes from direct electron impact [13]. Thus, the reaction rates are directly proportional to the electron density, while the rate constants are strongly dependent on the electric field value.

The local continuity equations for the excitation of the FNS and SPS by direct electron impact and their successive collisional quenching in a steady-state approximation can be written as follows [13]:

$$k_{x\rightarrow c}\, n_e\, [N_2] = \nu_C^q\, [N_2(C)] \tag{3}$$

$$k_{x\rightarrow B}\, n_e\, [N_2] = \nu_B^q\, [N_2^+(B)] \tag{4}$$

where $[N_2]$ is the ground level Nitrogen population number density, $[N_2(C)]$ and $[N_2^+(B)]$ are the population number densities of the upper levels that originate SPS and FNS respectively, n_e is the electron density, $k_{x\rightarrow c}$ and $k_{x\rightarrow B}$ are the rates constants of both excitation processes and ν_C^q, ν_B^q are the corresponding quenching rates. For atmospheric air density, the quenching rates are [13]:

$$\begin{aligned}
\nu_C^q &= 1.84\ 10^9\ s^{-1} \\
\nu_B^q &= 1.74\ 10^{10}\ s^{-1}
\end{aligned} \tag{5}$$

and the rate constants (in $cm^3\ s^{-1}$) are [13]:

$$\begin{aligned}
\log k_{x\rightarrow C} &= -8.87 - 228/\theta \\
\log k_{x\rightarrow B} &= -9.03 - 509/\theta
\end{aligned} \tag{6}$$

where θ is the reduced electric field $\frac{E}{N}$ in Td (1 Td = 1 10^{-17} V cm^2), with E the absolute electric field and N the total number density of air molecules. From (3) and (4) the intensity ratio under stationary conditions is,

$$\frac{[N_2^+(B)]}{[N_2(C)]} = \frac{k_{x\rightarrow B}}{k_{x\rightarrow c}} \frac{\nu_C^q}{\nu_B^q} \tag{7}$$

From this ratio the value of θ can be derived. For all the experimental conditions studied in this work, the value of the line intensity ratio was almost constant A statistical analysis performed over more than twenty spectra showed that this line amplitude ratio was 0.02 ± 0.004, and the value of θ obtained from (7) was 500 Td ± 100 Td.

5 FINAL REMARKS

The sliding discharge optical emission of the spectral bands corresponding to the 0-0 transition of the second positive system of N_2. (λ = 337.1 nm) and the first negative system of N_2^+ (λ = 391.4 nm) have been measured. Also the light spatial distribution in the plasma sheet has been studied using a CCD camera coupled to interferential filters corresponding to the wavelengths investigated.

Our experimental results indicate that the plasma light intensity depends slightly on V_{AC} but is almost independent on V_{DC} and f, at least within the reported range of values.

The increase in the light intensity, with V_{AC}, together with the quoted similar behaviour of the spectral line amplitudes (i.e. the constancy of the reduced electric field value) seems to be related to a more uniform light distribution in the gap, which in turn can be related to an increasing number of streamers bridging the gap when V_{AC} increases.

Moreover, a detailed electrical study of the SD has been shown that the streamer generation rate is well correlated with the mean SD current [9]. This fact suggests, together with the reduced electric field constancy, that the increase in the mean SD current with V_{AC} [9] is not associated with an increase in the amplitude of the individual streamers, but with an increase in their generation rate.

On the other hand, the fact that the plasma light intensity is almost independent on V_{DC} is in concordance with the previously observed behavior of the SD current with the V_{DC} value (i.e. the mean SD current is almost independent on V_{DC} for high enough V_{AC} values, for more details see [9]).

In order to find an explanation of the SD behavior with respect to the ac excitation frequency (*f*) we are currently studying the SD considering wider ranges of *f*.

A useful method of diagnostics has been employed to determine the reduced electric field in a sliding discharge.

The obtained reduced electric field, averaged in space and time, corresponds to that present in a central section of the upper electrode's gap outside the field of view of both electrodes (1 and 3).

The streamer mechanism has been proposed to explain the breakdown process at atmospheric pressure and at distances over 1 cm [14-15]. In this context the high value obtained for the reduced electric field must corresponds to the value of the reduced electric field present in a streamer head. Note that the predicted reduced electric field value in the streamer channel is one order of magnitude lower (i.e. 20-60 Td),so the strong dependence of the excitation rates with θ predicts that no radiation process can be found within the streamer channel. In fact, the detected light comes from the streamer head where the electron density and temperature are high enough to produce intense vibrational excitation and ionization of the molecules [16].

Using the air number density corresponding to normal conditions (N = 2.4 10^{19} cm^{-3}), the obtained θ value corresponds to an electric field value of E = 120 kV/cm. Although this value could be slightly modified by some gas heating by the discharge, such a high E value can be found under our experimental conditions only at the head of a streamer.

This result, together with the visual inspection of the SD (that looks like a diverging plume of several filaments with its vertex on the anode), indicates that the SD is composed of positive streamers (cathode directed) that fill the inter-electrode gap. When the external field exceeds the value required to sustain the streamer, a self-propagating head with a local electric field depending very little on the external field, propagates along the gap, producing and absorbing avalanches by its own [17].

Once the E/N value is determined, the plasma density can be obtained using the atomic model [13] if the absolute line intensity is known. This procedure was employed to estimate the streamer head density for the SD [9]. It is worth noting that the estimation of those SD parameters (i.e. streamer head electric field and plasma density) are essential to determine the coupling mechanisms between the SD and the flow to be controlled.

Using the obtained value for the electric field, it is possible to estimate the average value of the electron temperature (T_e) under the assumption that the electrons have enough time to reach an equilibrium value of its mean energy in the presence of the electric field. Even with this simplifying assumption, the T_e value strongly depends on the electron energy loses (in elastic and inelastic collisions) to the neutral particles, so we have resorted to a software package [18] for the numerical solution of the Boltzmann equation for electrons in weakly ionised gases and in steady state, uniform electric fields. Using air at atmospheric pressure and E = 120 kV/cm, it is obtained T_e = 9 eV.

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A. Márquez presently not available

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