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Experimental pressure dependence of positive corona discharge in N_2

R. Benocci[a], A. Galassi, L. Mauri, M. Piselli, and M. Sciascia

Università degli Studi di Milano-Bicocca, Dipartimento di Fisica "G. Occhialini", P.zza della Scienza 3, 20126 Milano, Italy

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Abstract. This paper presents the experimental pressure dependence, in the range $1.01\times10^5-1.6\times10^5$ Pa, of the $I-V$ characteristic of a N_2 positive corona discharge. The pressure raise is related to the gas flow increase into the chamber where the corona is ignited. Experimental measurements confirm Townsend's $I-V$ characteristic. For a fixed potential difference between the electrodes, corona currents decrease as the gas flow increases (pressure increase): this has been ascribed to a lower ionization rate close to the stressed electrode and a lower charge mobility in the drift region. Both these processes result in a lower current generated by the discharge.

PACS. 52.80.Hc Glow; corona

1 Introduction

Corona discharges are characterized by a highly non uniform electric field due to the small dimensions of at least one electrode (for example a point or a thin wire). The corona is said to be positive if the electrode where the electric field reaches the highest values is the anode, negative in case it is the cathode. The gap between the electrodes can be divided into two regions: the zone where ionization processes take place (in the proximity of the stressed electrode) is called ionization region; the remaining zone is called drift region because the electric field is weaker and the charges drift towards the opposite polarized electrode. Charge carriers in the drift region are thus positive ions in positive coronas, electrons in negative coronas (negative ions if the gas is electronegative). The relationship between the current I and the potential V applied to the electrodes has been derived by Townsend [1] in a coaxial cylinder geometry. In its general form, valid also for needle-to-plane geometry, the $I-V$ characteristic [2–4] can be written as:

$$I = kV(V - V_0) \tag{1}$$

where I is the corona current, V the applied voltage, V_0 the initial corona voltage and k a dimensional constant depending on geometrical parameters and the charge carrier mobility in the drift region. Equation (1) is also expressed in terms of I/V as a function of V, the so-called reduced characteristic (linear dependence):

$$\frac{I}{V} = kV(V - V_0). \tag{2}$$

The corona discharge has been investigated in many works [5–12] giving prominence to different discharge features according to the process gas, the polarity of the corona and its steady or pulsed mode of operation [5,6]; the influence of electrode geometry and gas flow rate in air [7]; the influence of chamber temperature [8]; ion mobility measurements [9]; optical emissions [10]; positive corona discharge in gas mixtures [11,12]. The present work outlines the pressure dependence of a steady-state positive corona in pure nitrogen. A needle-to-plane configuration has been studied: the needle is made of nickel-plated steel with a curvature radius $r \approx 20$ μm, the plane is a stainless-steel plate (diameter 10 mm). The distance between the electrodes is 1–2 mm, with a nitrogen gas flow rate in the range 1–10 slpm. The experimental dependence of equations (1, 2) on the chamber static pressure are also discussed.

2 Experimental setup

The corona discharge is ignited, as illustrated in Figure 1, in a closed chamber (**1**). The distance between the electrodes is regulated through a bellows. The chemically 99.999% pure nitrogen (**13**), is passed through a Tylan General FC280A mass flow controller (**10**) and a Monotorr PS3MT3N2 gas purifier (**9**) which reduces its impurity content (O_2, CO, CO_2, H_2, H_2O) to 1 ppb level. After this stage, the nitrogen flows into the corona chamber. During the system warm-up period, the outlet gas is vented through a purge line (**12**). The chamber is also connected to a vacuum system including a Rial Vacuum DPS 100/3-CF63 turbomolecular pump (**7**) and a Rial Vacuum

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[a] e-mail: `roberto.benocci@mib.infn.it`

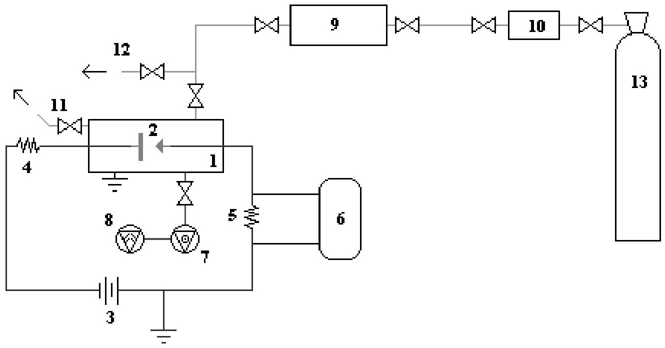

Fig. 1. Experimental setup.

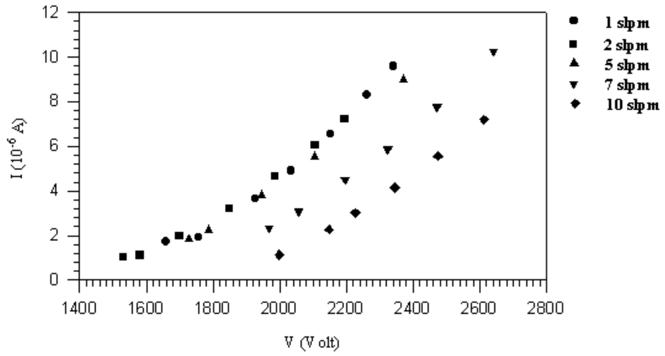

Fig. 2. $I - V$ characteristic, $d = 1$ mm.

Dry 3 dry rotary pump (**8**). The chamber is evacuated, before each experimental measurement, to keep always clean the chamber and electrode surfaces. The pressure is measured with a Leybold Membranovac total pressure gauge. The power supply (**3**) is a DC high voltage source up to 6 kV. The load resistance (**4**) is $R = 1$ MΩ with a current intensity ranging from 1 to 10 μA. Corona currents are recorded, at the ends of a resistance (**5**) $R = 10$ KΩ, using a LeCroy 9304 AM oscilloscope (**6**).

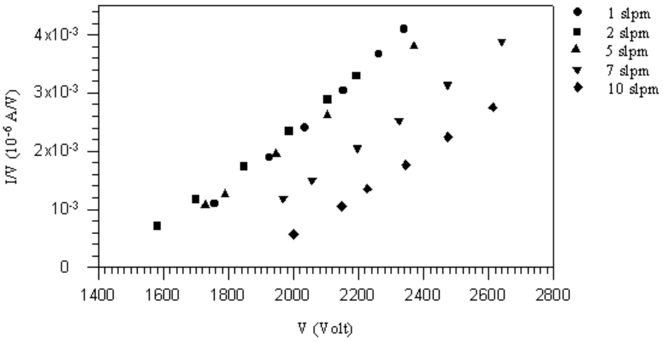

Fig. 3. Reduced characteristic: $I/V - V$, $d = 1$ mm.

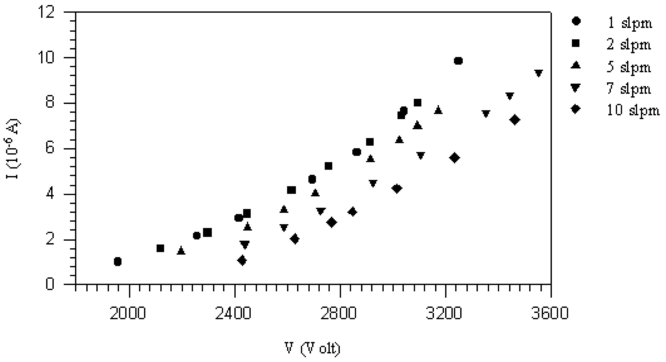

Fig. 4. $I - V$ characteristic, $d = 2$ mm.

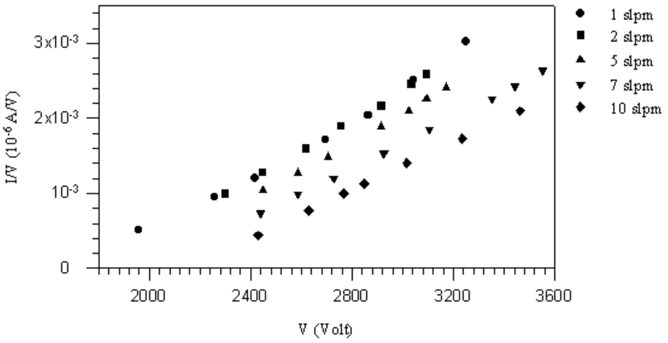

Fig. 5. Reduced characteristic: $I/V - V$, $d = 2$ mm.

3 Results and discussion

The $I - V$ characteristic of the discharge has been investigated with 2 different electrode distances: 1 mm and 2 mm. The corona current ranges between $I \approx$ 1–10 μA in all tests. Experimental $I - V$ data (Figs. 2 and 4) and the reduced characteristic (Figs. 3 and 5) are presented for different gas flow rates. Referring to Figure 2, raising the nitrogen flux from 1 to 10 slpm (pressure increment from 20 to 550 mbar), the current decreases from $I \approx 9.5$ μA to $I \approx 4$ μA for $V \approx 2300$ V. Considering nearly the same voltage $V \approx 2400$ V for $d = 2$ mm, Figure 4, the corona current passes from $I \approx 3$ μA to $I \approx 1$ μA if the gas flow rate increases from 1 slpm to 10 slpm. This shows that the current, for a fixed potential and flux rate, decreases as the distance between the electrodes is increased. This can be explained by Paschen's law because the pd product increases (being p the working pressure and d the distance between the electrodes), for a fixed pressure, with the distance thus increasing the breakdown voltage V_b. For the operative condition investigated, pd values are beyond $(pd)_{\min}$ corresponding to the minimum breakdown potential [13]. As the discharge has a positive resistance, the breakdown voltage goes up with the distance d thus reducing the current produced by the discharge. This condition holds for any potential difference $\Delta V \geq V_b$.

Experimental data follow the trend predicted by equations (1, 2). The linear dependence of the reduced characteristic (Figs. 3 and 5) confirms Townsend's approximation: the space charge does not affect the electric field between electrodes. Therefore, the following considerations can be made in terms of the electric field resulting from the Laplace's equation solution.

The flow dependence is related to a pressure increment into the chamber as the flow rises. Figure 6 shows the

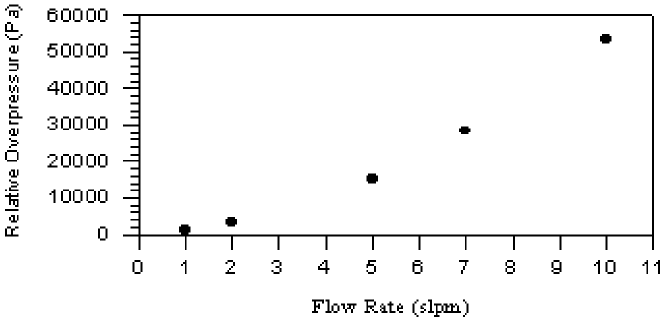

Fig. 6. Relative pressure increase as a function of N_2 flow rate.

relative chamber overpressure $p_1 - p_0$ (p_0 is the atmospheric pressure) as a function of gas flow rate.

The chamber overpressure raises from 10^3 Pa at 1 slpm to 5.5×10^4 Pa at 10 slpm. The gas flow rate, that is the viscous regime, is not supposed to affect the discharge in the ionization region, which is characterized by an intense electric field ($E \approx 10^7$ V/m), therefore with high drift velocities of charges. However, most part of the gap is occupied by the drift region where the electric field is lower ($E \approx 10^5$–10^6 V/m). Let v_g be the average gas velocity and v_{id} the ion drift velocity moving towards the cathode, in this case $v_{id} \gg v_g$, being $v_{id} = \mu_i E \approx 10^1$–$10^2$ m/s ($\mu_i \approx 10^{-4}$ m^{2}V^{-1}s^{-1}), whereas $v_g = F/S \approx 10^{-1}$ m/s, where F is the nitrogen flux and S is the chamber cross section area. Molecules, therefore, do not interfere ions drift motion and do not affect their mobility: forward scattering of ions is not influenced by the velocity component of gas in the drift directions of ions.

The pressure increase causes a variation of the ionization coefficient α, in the ionization region, and a variation of the ion mean free path length λ, in the drift region, for a fixed potential voltage value V between the electrodes. The ionization coefficient is given by [2]:

$$\alpha = Ap\mathrm{e}^{\frac{-Bp}{E}} \tag{3}$$

where the constants A and B are [2]: $A = 9$ m^{-1}Pa^{-1}, $B = 257$ Vm^{-1}Pa^{-1}. As the pressure goes up, α decreases, thus producing a lower ionization rate close to the tip. As a consequence, the current generated by the corona discharge decreases. Referring to Figure 4 and considering, for example $V' = 2400$ V, the electric field can be evaluated by solving the Laplace equation in the given configuration. Figure 7 shows the electric field components E_x, E_r and the ionization coefficient α along the symmetry axis (x) and in the radial direction (R) calculated for $d = 1$ mm (the needle tip is placed at $x = 1$ mm, whereas the plate at $x = 2$ mm). As one can imagine the electric field strength is higher in the tip proximity with values of $E_x = 1.7 \times 10^7$ V/m, $E_r = 1.3 \times 10^7$ V/m and $\alpha = 2.2 \times 10^5$ m^{-1}, and rapidly decreasing turning away from the needle.

Figure 8 shows the ionization coefficient per unit pressure, α/p, as a function of the reduced field E/p.

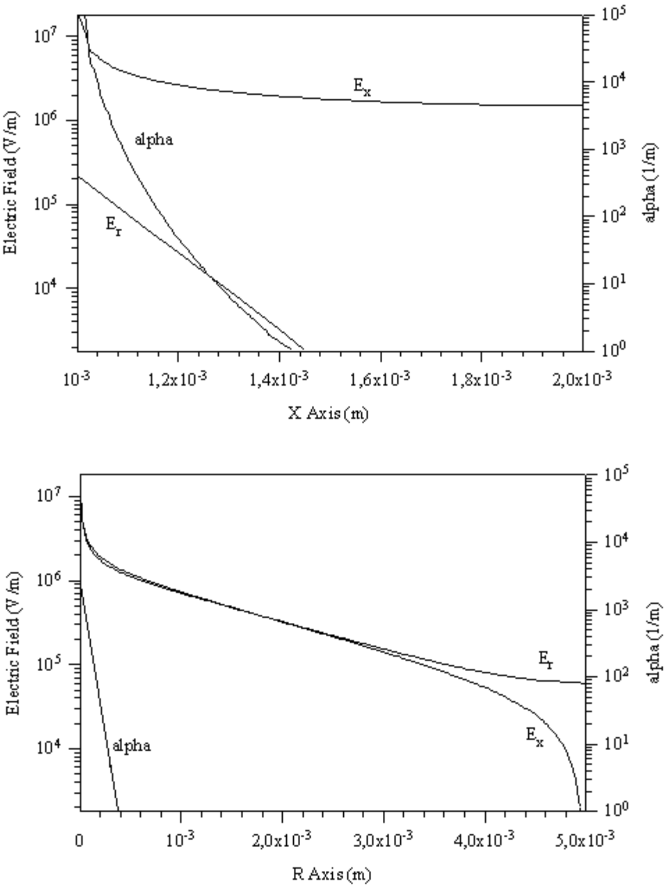

Fig. 7. Electric field components E_x, E_r and ionization coefficient α along the symmetry axis x and in the radial direction R.

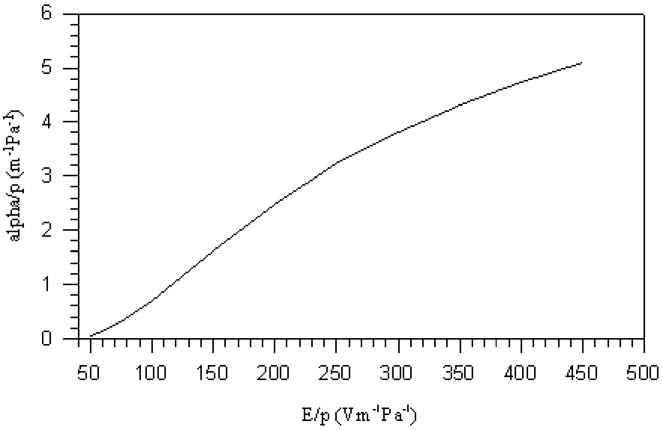

Fig. 8. Ionization coefficient per unit pressure α/p as a function of the reduced electric field E/p.

Increasing the pressure inside the chamber, for a fixed value of the electric field E, E/p decreases and consequently α/p diminishes.

Taking for the electric field in the ionization region a value of $E \approx 10^7$ V/m, the ratio E/p_0 and α/p_0 are respectively: $E/p_0 \approx 99$ Vm^{-1}Pa^{-1} and $\alpha/p_0 \approx 0.67$ m^{-1}Pa^{-1}, being p_0 the atmospheric pressure. When the flow is raised up to 10 slpm, the pressure inside the chamber reaches the value $p_1 \approx 1.545 \times 10^5$ Pa and $E/p_1 \approx 65$ $\mathrm{Vm^{-1}Pa^{-1}}$, $\alpha/p_1 \approx 0.17$ $\mathrm{m^{-1}Pa^{-1}}$. Moreover, the ion mean free path length λ is inversely proportional to the gas density: $\lambda = 1/(4N\sigma) \approx 10^{-4}$ m at atmospheric pressure (σ is the cross-section of N_2 molecule) is assumed to be equal to the molecular mean free path length because the gas is weakly ionized. Increasing the pressure, λ diminishes and the collision frequency ν_c increases thus reducing the ion mobility: $\mu_i \propto \nu_c^{-1}$.

4 Conclusions

The experimental data exposed in the present work have been devoted to outline the pressure influence on the $I - V$ characteristic of a positive corona discharge. A pressure increase in the discharge gap, for a given value of the electric field, reduces the ionization rate processes in the ionization region and the ion mobility, in the drift region, diminishes. These two effects bring to a decrease of current circulating in the external circuit. For nitrogen gas flow rates of 1–2 slpm the pressure increase is not significant (≈10 mbar) therefore the ionization processes and ion drift motion are unchanged. In case the gas flow rate is raised over 5 slpm the overpressure becomes important and the current decreases significantly.

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