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Ion current density profiles in negative corona gaps versus EHD confinements

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ABSTRACT

This paper deals with the electric and hydrodynamic confinement of negative ions in a point-to-plane corona discharge gap. Radial ion current density profiles have been measured on the earthed planar electrode, drilled in the axis of the point. The experimental setup is first validated by comparison with the Warburg's law without injected gas flow rate. The gas injected in the gap and blown from the discharge gap through the hole located at the centre of the plane affects neither the electric field close to the point nor the subsequent electric wind. However, it leads to the confinement of ions flux towards the central symmetry axis in the low electric field region up to a critical gas velocity, which for no more effect is measurable. Hence, electro hydro-dynamics confinement of ions can be achieved by limiting the outward radial expansion of ions to increase ion current densities on specific locations close to the low field planar electrode.

1. Introduction

Thanks to various electrode configurations and operating conditions, Coronae are used for electrostatic filtration and separator [1–3], chemical analysis [4], ozone generation [5], heat and mass transfers [6–7]. For all these applications, controlling the ion fluxes in the gap is critical to control the process. With the self-induced "ion wind" (cf. §2) and no injected gas flow, the radial distribution of ions in the low field region close to the planar electrode, related to the current density measured on the earthed plane is known to evolve with the applied voltage of the point and versus the geometry of the gap [8]. Thus, many modelling works have been developed to study the Electro-Hydro-Dynamics (EHD) flow in coronaes to account for the self-induced ion wind [9-10].

In this work, a point-to-drilled plane corona discharge is used to produce negative ions for aerosol charging downstream the discharge gap, hereafter referred as post-discharge. As proposed by Whitby to avoid aerosol losses by electro-collection in the gap [11] and still under investigations [12–14], a gas flow is used to blow ions from the gap through a hole drilled in the earthed electrode to the post-discharge charging zone. This implies aerosol charging in much lower post-discharge ion densities than in the gap. The mean number of charges per particle depends on the particle diameter and on the $N_i.t$ product (with N_i, the ion density and t the transit time of aerosol in this ion density). Post-corona unipolar aerosol chargers thus usually lead to higher charged aerosol concentration, but to lower mean number of charges per particle than when aerosol is injected in the discharge gap. To increase the ion density in the post-corona charging volume, the effect of the gas flow on ion extraction has been studied.

Since the ion flux extracted from the discharge gap necessarily depends on the ions density distributions in the gap, this paper focuses on the effect of the gas flow velocity on the current density and on the electric field in the gap, especially just next to the extraction hole drilled in the low field planar electrode, as already described with a gas flow perpendicular to the point axis [15] or in a wire-to-plates electroprecipitator [16].

After an introduction of the theoretical background on EHD induced by ion fluxes in a discharge gap, the experimental set-up is first validated and calibrated to account for the effects of the connection tracks and of the insulating surfaces between these conductive tracks used for ion current density measurement on the low field drilled planar electrode. Then, the effect of the gas flow on the radial distribution of ion current density measured on the earthed plane ($j(r)$, the current density profile in $A.m^{-2}$) is presented and discussed for different applied voltages, point radii and

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gap lengths.

Doing so, both electrostatic and hydrodynamic confinement of ions in the central axis of the point close to the low field drilled planar electrode are reported and discussed.

2. Theoretical background of the study

In negative point-to-plane corona, the negative ions produced by the plasma are accelerated by the Coulomb force and move towards the grounded plane. The high-frequency collisions between ions and neutral air molecules slow down ions and produce the EHD gas flow, known as the ion or electric wind [17]. The ions drift velocity is given by $\mu_i.\overrightarrow{E}$ with μ_i the mean mobility of ions, $\overrightarrow{E}$ the electric field. In each point of the gap, the ion current density depends on the electrostatics drift, advection and diffusion:

$$\overrightarrow{j} = N_i \cdot \left(\mu_i \cdot \overrightarrow{E} + \overrightarrow{v}\right) - D_i \cdot \nabla N_i \tag{1}$$

where N_i is the ion density, $\overrightarrow{v}$ the gas velocity and D_i, the mean diffusion coefficient of ions. In most cases, the diffusion process can be neglected. Moreover, the gas velocity (related either to the ion wind or to the injected air flow, most often below 10 $m.s^{-1}$) can be neglected compared to the electrostatic one (above 10 $m.s^{-1}$).

In 1889, Warburg has measured the current density profile in a point-to-plane corona discharge, with the self-induced ion wind and without injected gas flow. To do so, an earthed plane made of flat concentric metal rings has been used to define an empirical law [8]:

$$j(r) = J(0) \cdot \cos^m \theta(r) \quad \text{for}\ \theta < 60°, \tag{2}$$

$$j(r) = 0 \quad \text{for}\ \theta \geq 60°;$$

$$\text{with } J(0) = \alpha \cdot V \cdot (V - V°)/d^n \sim I/\left(k \cdot d_{gap}^2\right)$$

where $J(0)$ is the axial peak current, θ is the semi-vertical cone angle of the discharge given by: $\theta = tan^{-1}\ r/d_{gap}$. where r is the radial planar coordinate and d_{gap} is the gap length. Warburg and other authors [8,18–19] define the power m and the coefficient k ($m = 4.82$ for positive polarity and 4.65 for negative polarity and $k \sim 2$). The Warburg's law is the result of the EHD competition in the discharge gap controlling the transport of ion. Electrostatic forces depend on the electric field (Laplace and space charge fields). Hydrodynamic forces depend on the relative velocity of ion and neutral molecule, controlled by the electric wind [20].

Warburg's law, set for centimetre gap, has been confirmed for millimetre and centimetre gaps [9,17,21,22] up to several meters by Allibone [23]. Goldman et al. have reported some dimples in the axial peak current and defined an approximation of the axial peak current $j(0) = I/k\ d_{gap}^2$, with $k = 2$ [19]. Theoretical EHD analyses have been conducted by Sigmond [20] and Jones [24] with examples given in Refs. [9,25,26].

3. Materials and methods

The experimental set-up is depicted in Fig. 1. The measurements are carried on at room temperature between 18 and 25 °C.

The active electrode (metal point) is a tungsten needle with a radius of curvature from 26 to 132 μm. The earthed electrode is a printed circuit board composed of seventeen concentric copper rings (width between 1.5 and 1.625 mm) insulated from each other by a 0.5 mm width epoxy resin.

The point is connected to a negative high voltage power supply through a resistor ($R_{ballast} = 10\ M\Omega$). This resistor induces a voltage

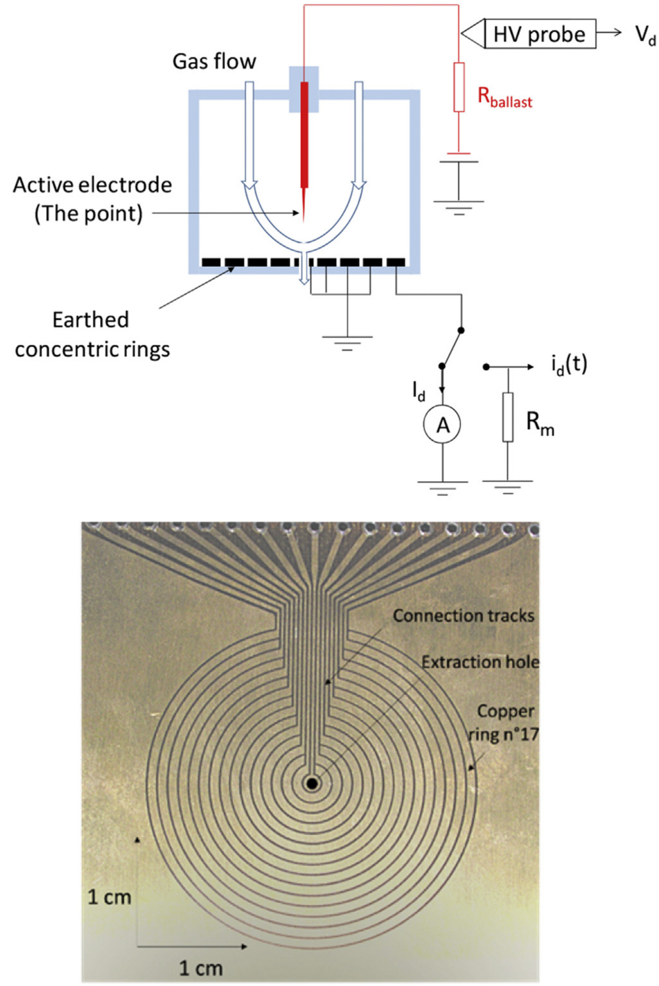

Fig. 1. Experimental setup used for discharge characterization and current density profile measurements.

drop ($\Delta V = R_{ballast}.\ I_{discharge}$). The voltage of the point (V_d, in V) is measured with a high voltage probe. The discharge current (I_d, in A) is measured with all the rings connected to an electrometer and visualised with an oscilloscope through a resistor (R_m). A resistor of either 50 Ω or 10 kΩ is used for the characterization of the Trichel pulses and the mean discharge current respectively. Both negative current and voltage are given and plotted in absolute value.

The distance between the walls of the cylinder and the point ($D_{walls\text{-}point}$) is chosen to limit the modification of the radial electric field and the related ion distribution in the gap ($D_{walls\text{-}point} = 65\ mm > 5.d_{gap}$). The pressure in the gap is 1020 mbar, whatever the gas flow rate is.

The clean and dry air flow (without aerosol, concentration of volatile organic compounds < 10 ppmv, relative humidity < 5%) is controlled by a mass flow metres from 0 to 30 $L.min^{-1}$. The gas flow is injected far above the point (150 mm) on the whole section of the reactor using grids to reach laminar flow. The injected gas velocity around the point is about 1 $m.s^{-1}$, far below the ions one (~100 $m.s^{-1}$).

To compute the $j(r)$ profile, the current of each metal ring is divided by the apparent areas (A_i') of the ring (as detailed in §4.1.2 and Table 1). The current density profiles are plotted versus the mean radius r_i of each ring calculated by $r_i = (r_i^{-1out} + r_i^{out})/2$ with r_i^{out} the outer diameter of the i^{th} ring, for $1 < i \leq 17$. Using these mean radii as abscises of $j(r)$ to plot the values calculated as