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Discharge characteristics of plasma sheet actuators

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Abstract
The electrical characteristics of a plasma sheet device used for subsonic airflow control are studied in this paper. Experiments are undertaken with a two-wire asymmetrical (different diameters, opposite polarity) electrode configuration connected to dc high voltage sources in the presence of a dielectric plate and under different gases (dry air, nitrogen and oxygen). For large distances electrode-plates it has been found that the discharge current consists of a purely dc component. The proximity of the plate reduces notably this dc current component until a limit situation for which the electrodes practically lay on the plate and a current pulsed regime is superimposed on the dc (small) component, thus establishing a plasma sheet regime. This regime could be reached only when the small wire was positive. This work establishes that the pulsed regime may be associated with a succession of positive streamers (cathode directed) which formation is promoted by different parameters of the gas and surface characteristics (thresholds of photoionization and photoemission, charge deposition,...). The dc component seems to be produced by a small number of electrons originated in the ionization region of the negative corona that are amplified in the ionization region of the positive corona. The charged particles produced during the streamer propagation could contribute appreciably to the ion momentum transfer to the gas. This transfer should be due very likely to the drift of the charged species present in the streamer channel during the streamer collapsing phase. The source of momentum transfer associated with the dc current would always persist with a magnitude that depends on the intensity of this current.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The number of research efforts dedicated to the study of electro-hydrodynamic (EHD) actuators for flow control in aeronautical applications has been increasing in the last years. Through the ionization of flowing air close to the surface of the body, EHD devices produce a modification of the condition of the flow at the wall. As a consequence of the elastic collisions between the migrating charged particles and the neutral species of the gas, the neutrals increase their momentum giving rise to an 'electric wind' in the close vicinity of the wall. When the number of charged species is high, other mechanisms may add to this electromechanical coupling like alterations of the physical properties of the gas (density, viscosity, etc) in the regions of ionization that are very close to the flow boundaries (Scherbakov *et al* 2000). In EHD devices the magnetic forces are negligible when compared with the electric ones because the actuation is produced with very low current intensities, and they are attractive from a technological point of view because

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of their simplicity (they have no moving parts) and their very short response time (delays in the establishment of a discharge are theoretically of the order of nanoseconds for appropriate values of the driving voltage).

EHD actuators can be ordered in three large groups based on the different electrical characteristics of the discharge: dielectric barrier discharge devices (DBD); unipolar coronas based devices (UCD) and plasma sheet devices (PSD).

From the pioneering work of Roth and his group at the University of Tennessee (Roth *et al* 1998, Sherman 1998) a large number of studies of flows actuated with DBD have been carried out (see, for instance, Corke *et al* 2002, Corke and Chuan 2004, 2005, Roth and Sherman 2000, Roth 2003, Roth and Xin 2006, Wilkinson 2003). These actuators use periodically excited electrodes, one of them exposed to the air while the other is encapsulated in a dielectric material. The dielectric barrier interposed between both electrodes serves to stabilize the discharge, thus avoiding the impact of the ions on the cathode and preventing its heating and the formation of new avalanches through secondary electron emission. Usual configurations consist of planar parallel electrodes separated by a thin dielectric film situated in an arrangement in the span-wise direction of an aerodynamic surface. In order to achieve a self-sustaining discharge DBD devices require a cyclic excitement with excitation frequencies in the range of some kHz. The discharge is revealed by a diffuse light indicating that the ionization process occurs in the close vicinity of the air-exposed electrode.

UCD are characterized by one active electrode surrounded by an ionization region where free charges are created and low-field regions with a large accumulation of space charge where charged particles drift and react in their movement towards the passive electrode. Reports of flow control actuated with UCD in view of aerodynamic performance improvements for subsonic regimes date from the 1980s (Bushnell, 1983 and Malik *et al* 1983, Van Rosendale *et al* 1988) and were further continued at the University of Poitiers in the 1990s (Noger *et al* 1997). In these studies a corona point-to-plane was intended to actuate the flow, but efficiency problems were apparent. Other studies with parallel wires or razor blade electrodes arranged on small flat plates (Soetomo 1992, El-Khabiry 1994, El-Khabiry and Colver 1997, Colver and El-Khabiry 1999) have been also performed under the scope of airflow control.

The use PSD devices to achieve flow control were first proposed by a group of the University of Buenos Aires (Desimone *et al* 1999, Artana *et al* 1999, 2000) and an important number of subsequent efforts were continued at the University of Poitiers (Leger *et al* 2001, 2002, Leger 2003, Moreau 2004, Moreau *et al* 2004, 2006). The sheet is produced with two air exposed electrodes mounted on the surface of a dielectric body. The electrodes excitation can be produced with dc or with a periodic voltage source that is adjusted to produce an ionization process occupying the whole inter-electrode space. In this region the surface appears streamlined by a thin film of ionized air or plasma sheet. The currents of plasma sheets include a dc component and a large number of peaks with frequencies of the order of some kHz. (Moreau *et al* 2004)

More recently, a new sub-group of PSD discharges named sliding devices (SD) has been developed in a joint effort between the groups of the University of Buenos Aires and the University of Poitiers. These devices may produce stable plasma sheets (Louste *et al* 2005) but require the use of at least one ac power supply. The electrode configuration was suggested by a previous work concerning the study of pulsed discharges in the context of laser research (Lagarkov and Rutkevich 1993). It consists of two air exposed electrodes and a third one separated by a dielectric barrier. One of the electrodes is excited with an ac voltage source and the others are connected together either to a dc voltage source or grounded. The discharge behaves like a planar streamer with an ionization wave largely influenced by the normal electric field to the surface. The electrical characteristics and aerodynamic performance of these devices with cyclic excitations are presently under study.

Bipolar coronas may be produced using two electrodes with small radii of curvature, and applying high voltages of opposite polarity to both electrodes. This discharge has in consequence a positive and a negative ionization region. Another possible scenario of bipolar coronas may also take place even when only one electrode of small radius of curvature is used, as in point-to-plane electrode arrangements. In these cases at high corona currents the electric field may be disturbed by the space charge in such a way that a field rise is produced on the passive electrode high enough to provoke ionization in the vicinity of this electrode.

Hence in a wire-to-wire electrode arrangement both kinds of bipolar scenarios may take place depending on the electrodes potentials and diameters.

The characteristic unipolar conduction currents (glow coronas) that flow when only one electrode is active (negative or positive) continue flowing also in coronas with characteristic bipolar conduction phenomena present. The unipolar conduction mechanisms are often called the continuous current (dc) as their oscillations are of high frequencies and are smeared out by the slow movement of ions through the drift region. When current pulses appear it seems that this dc current is unaffected by its presence (Goldman and Sigmond 1982); however, both currents may be quite sensitive to external parameters like the presence of an insulating surface in the proximity of the active electrode (Akishev *et al* 2005).

Data on wire-to-wire discharges are unfortunately rather scarce. After the pioneering works (Peek 1929), to our knowledge, very few analyses have been reported with this kind of arrangement. Because of the interest in transmission lines, a similar configuration rather well studied has been the wire-to-wire but with a shield plate or cylinder in proximity (see, for instance, Al-Hamouz *et al* 1998).

The electrode configurations used to obtain plasma sheets with dc excitations, when not suitable, tuned into plasma sheet regimes, may produce other discharge regimes that are the same as the one observed with bipolar corona discharges in the first kind of scenario (ionization regions concentrated only at close vicinity of the electrodes). An important number of works related to flow control have also been reported for this kind of regime (Leger *et al* 2001, 2002, Moreau *et al* 2005).

The plasma sheet regime shows simultaneous characteristics of bipolar corona and other discharge regimes with the signature of surface discharges (discharges over insulating surfaces). This last kind of discharge produces in most cases a diffuse discharge or filaments consisting of positive streamers skimming the surface (Chiba *et al* 2002). The surface discharges have been proposed to be of the same nature as discharges propagating in bulk gases. However, the presence of the surface may influence the discharge propagation by modifying the electric field through polarization (or charge deposition) of the surface material or by the release of electrons from the surface as a consequence of photo-ionization. (Chiba *et al* 2002, Odic *et al* 2006).

Even though different kinds of electrode configurations and voltage excitations produce different discharges, it has been postulated in a recent article (Boeuf and Pitchford 2005) that the force f acting on the neutrals in a DBD is of the same nature as in a UCD. This claim is based on the fact that in a UCD the plasma is generated in a small volume around the small electrode, and the electric wind is a result of the momentum transfer from ions to neutrals in the non-neutral region outside the ionization region where the ions drift towards the large electrode. The situation is similar in a DBD, but the region where the force is non-zero (sheath) is much smaller and the force per unit volume is much larger.

The expression proposed by Boeuf and Pitchford for force f

$$f = \frac{j_i}{\mu_i}$$

(with j_i the ion current density and μ_i the ion mobility) unifies the action characteristics of the UCD with DBD but cannot be directly extrapolated to bipolar CD or PSD.

From an aerodynamic point of view, it can be argued that as the results obtained in similar models actuated with DBD have similarities with those actuated by PSD the forces produced by both devices could not differ largely.

Indeed an evaluation of the force produced with PSD requires an appropriate knowledge of the physics of the involved discharge. It is in this sense that there exists an important difference between PSD and DBD. With these last kinds of devices there have been a large number of articles that enable one to understand the nature of the DBD discharge while with a few exceptions much less efforts have been reported for the plasma sheet regime.

The aerodynamic performances of PSD as plasma actuators have been reported in previous works for different flow conditions (Artana *et al* 2002, 2003, D'Adamo *et al* 2002, Sosa 2004, Sosa and Artana 2006, Sosa *et al* 2006, Leger *et al* 2001, 2002, Leger 2003, Moreau *et al* 2005, 2006) but the electrical characteristics of plasma sheet regimes appear in a limited number of articles. Some previous reports concern voltage current measurements under different electrode configurations (Artana *et al* 1999, Moreau *et al* 2004), atmospheric conditions (Louste *et al* 2004, Moreau 2004), or surface materials (Louste *et al* 2004).

Some of these reports have shown that the plasma sheet current is a superposition of a dc component and peaks (Moreau *et al* 2004). However, it has not been clearly established which of these components should be maximized in order to increase the electromechanical coupling between the discharge and the airflow.

We propose here to compare several characteristics of corona discharges with the one that takes place when a plasma sheet is produced with dc excitation. The analysis is carried out

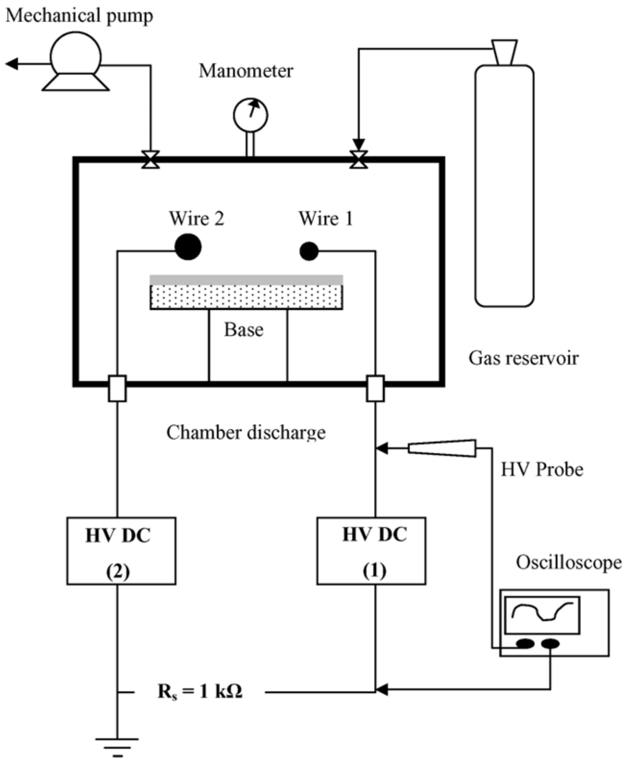

Figure 1. Experimental arrangement.

considering a wire-to-wire electrode configuration. Our study is focused on the electrical characteristics of the discharge under different controlled gas atmospheres and on the changes introduced by an insulating surface in the proximity of the ionization region. This study is done with the purpose of understanding the discharge characteristics rather than optimizing the actuator's geometry.

The study is complemented by a measurement of the pressure induced by the electric wind on the electrodes proximities. The paper is organized as follows: in the first section we describe the experimental set-up; in the following section we show the influence of the wall proximity on the electrical phenomena and on the induced electric wind; finally a section is dedicated to the analysis of the results and to the conclusions that can be obtained from this work.

2. Experimental set-up

The electrode arrangement of our experiments consisted of two parallel tungsten wires 150 mm in length and separated at distance $D = 30$ mm. The diameters of the wires were 0.5 and 1.5 mm and are referred to as wire 1 and wire 2, respectively. They were tested at different voltages and polarities ($V_1 V_2$) by means of two dc high voltage sources of opposite polarity (+20 kV, −20 kV, 0.5 mA). In all the experiments a dc positive high voltage to one electrode and a negative to the other were applied.

A schematic layout of the experimental set-up is shown in figure 1. The electrodes were placed in a gas discharge chamber in order to evaluate the discharge behaviour for different gases.

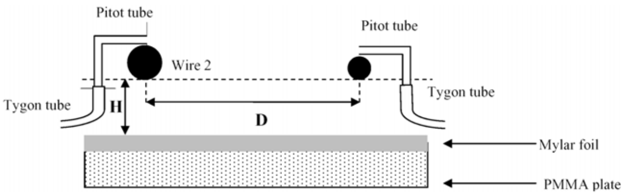

Figure 2. Electrode geometry.

The discharge chamber was a PMMA hollow cylinder with two end plates. The height of the chamber was 130 mm, the radius 200 mm and the wall thickness 6 mm.

A differential manometer that ranged from −0.1 to 0.3 MPa with a precision of 0.005 MPa was employed for gas pressure measurements. The chamber gas 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. In our tests we decided to avoid a renewal of electrodes and all tests have been carried out with the same electrodes. On the other hand special care was taken during the pumping or filling of the chamber with purified gases (up to 99.9%), but no measurements of gas composition has been performed related to traces that could be present on the gases used in our study (Air, O_2, N_2, Ar).

The electric current flowing in the system was measured with a 1 kΩ shunt resistance connected to an oscilloscope of 1 Gs s^{-1} (shown in figure 1). The electrodes voltage drop was measured with a HV probe (1000× /3.0 pF/100 MΩ).

Figure 2 shows the electrode geometry. A PMMA plate (8 mm thickness) covered with a Mylar foil (50 μm thickness) was located at a distance H from the parallel wires. The ensemble was supported by a base which can be displaced in order to modify H from 0 to 60 mm.

To analyse the induced ionic wind, two pressure probes (Pitot tubes) were placed as shown in figure 2. This pressure ports were made of glass tubes of 0.97 mm and were connected by means of tygon tubes to a differential pressure transducer. The employed pressure transducer was one of a variable reluctance type allowing one to measure up to 55 Pa with accuracy 0.25% full scale. The reference pressure value was that existing in the chamber far away from the electrodes. The pressure ports were placed in the middle of the wire lengths and in some cases displaced in order to evaluate the uniformity of the induced wind. The gas flow inside the chamber was stopped during pressure measurements.

In our experimental study we have associated the registered modifications in pressure to the airflow induced by the momentum transfer of ions to the neutrals (ion wind). Any spurious flow velocity associated with recirculation in the chamber was not considered. This hypothesis was not verified in all experiments but tests undertaken with air in open chamber conditions have shown similar results.

Optical images of the discharge were recorded with a digital camera Nikon Coolpix 5400 in a darkened room and at different times of expositions depending on the discharge light intensity.

3. Experimental results

3.1. Discharge characteristics

When the voltage was applied to the circuit the dc current had an initial value that decreased with time exponentially and asymptotically to a quasi-steady value. This kind of behaviour was reported previously with a time constant that depended on the material of the surface (Louste *et al* 2004). In our case the time required to achieve the quasi-steady-state was about 30 s. As this time changes with H, to allow a comparison among experiments at different H values, the results shown in what follows correspond only to the quasi-steady dc component measured at a time equal to 60 s.

In practice it was found that for $H > 13$ mm the discharge characteristics were insensitive to the particular H values.

In figure 3 the dc current (I_c) versus the inter-electrode voltage drop (ΔV) for different H values when the gas of the chamber was dry air are shown. Figure 3(*a*) represents the situation $V_1 = +10 - +20$ kV, $V_2 = -10$ kV, while figure 3(*b*) corresponds to $V_1 = -10$ kV, $V_2 = +10 - +20$ kV. Several discharge images are also shown in the figures. In all the situations the images reveal that ionization occurred in both the electrodes, and bipolar conduction phenomena were taking place. The graphs also show that when $H > 0$, and for a fixed voltage difference, the proximity of the wall produces a decrease of the dc current. The situation for $H = 0$ corresponds in experiments of figure 3(*a*) to stable plasma sheet configurations. As can be observed from this figure at lower voltages the plasma sheet configuration produced higher currents than those corresponding to $H > 0$. Sporadic plasma sheet configurations could also be observed for $H = 2$ mm for the same configuration of figure 3(*a*).

When the small wire was negatively stressed no plasma sheet was observed (figure 3(*b*)). It is worth noting that without the presence of the plasma sheet the discharge current was purely dc, but in the presence of the plasma sheet the current was a superposition of two components: a pulsed current and a dc current in agreement with previous works (Moreau *et al* 2004). A comparison of the current values of figures 3(*a*) and (*b*) shows that the small wire when positive stressed gave rise to the same voltage differences to lower currents than those obtained in the opposite situation. This behaviour is similar to that usually obtained in UDC with point-to-plane geometry.

Figures 4(*a*) and (*b*) show results of similar experiments when the chamber was filled with oxygen. The influence of the plate to electrode distance was similar to the one observed when the chamber was filled with air. However at $H = 0$ no plasma sheet could be obtained with oxygen and the purely dc current dropped to an almost null value whenever the polarities of the small wire were considered. For a given voltage drop, the resulting currents for $H > 0$ were higher than those obtained with the air tests. This occurred even when a saturation of the current originated by power supply limitations was observed at the larger voltage differences.

As can be seen in figures 5(*a*) and (*b*) the adjustment of the results for $H > 0$ presented in figures 3(*a*) and 4(*a*) with an expression of quadratic dependence of currents with electrode voltage of the type $I_c = C\Delta V\ (\Delta V - V_o)$ (where C and V_o are constants) fitted correctly the experimental values for the lower voltages range.

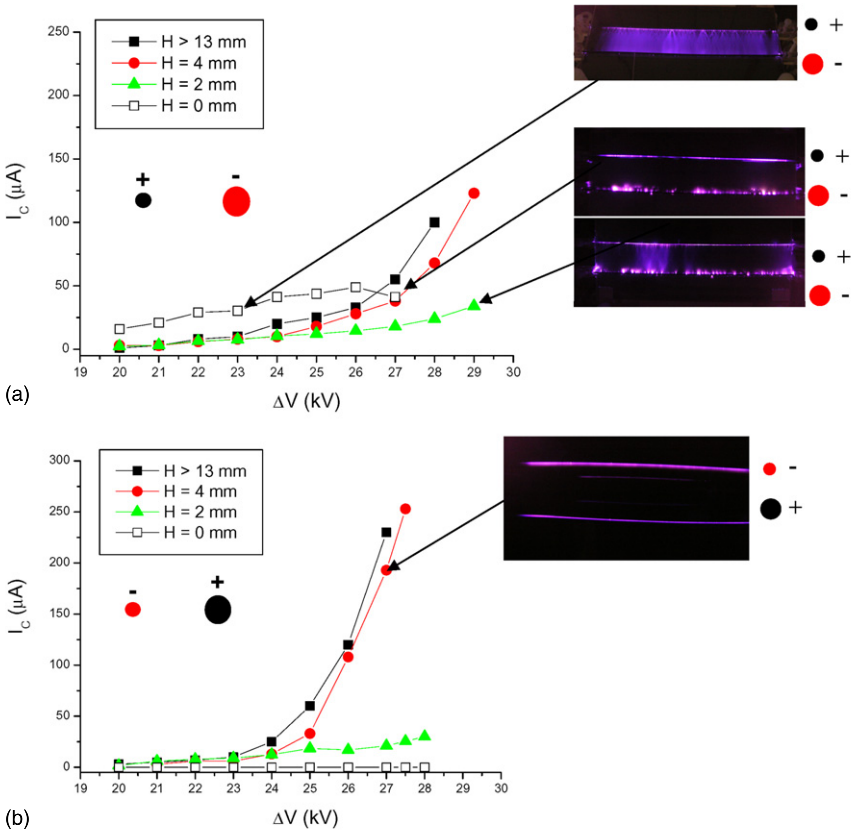

Figure 3. (*a*) I_C versus ΔV for different H values; gas: dry air; $V_2 = -10$ kV. (*b*) I_C versus ΔV for different H values; gas: dry air; $V_1 = -10$ kV.

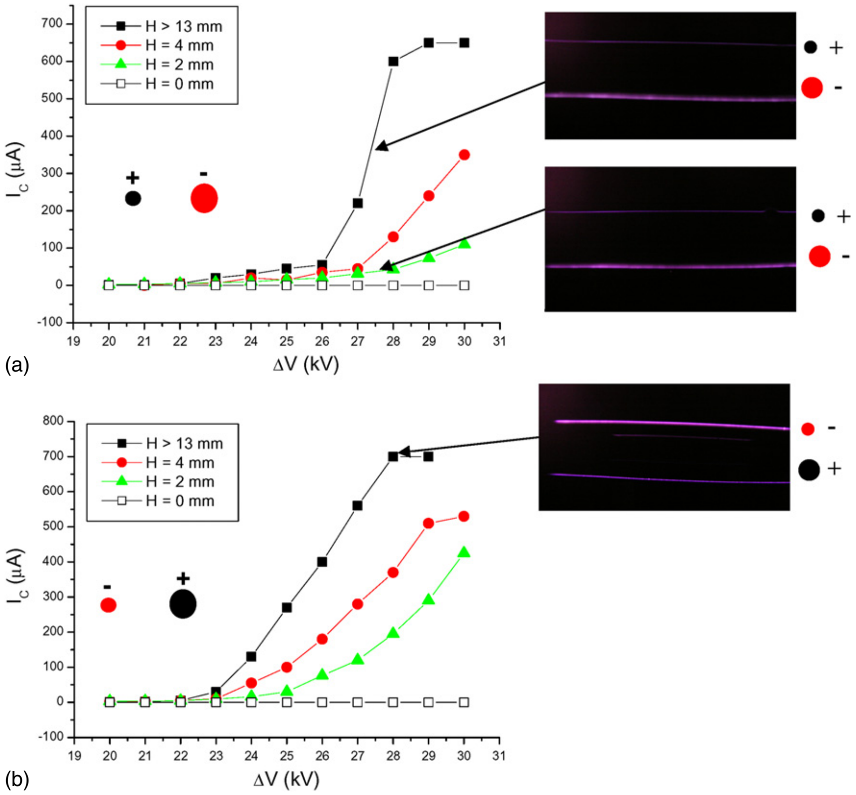

Figure 4. (*a*) I_C versus ΔV for different H values; gas: O_2; $V_2 = -10$ kV. (*b*) I_C versus ΔV for different H values; gas: O_2; $V_1 = -10$ kV.

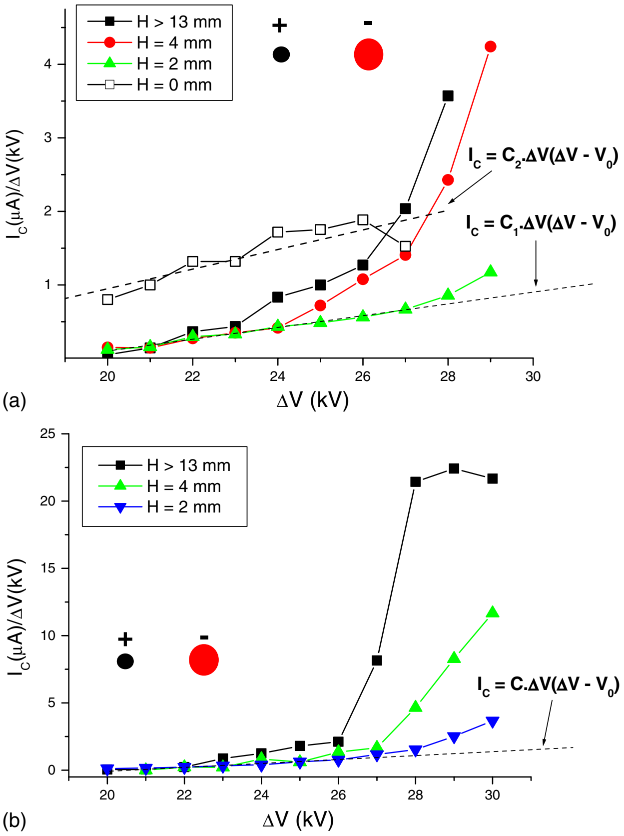

Figure 5. (*a*) $I_C/\Delta V$ versus ΔV; gas: dry air; $V_2 = -10$ kV. (*b*) $I_C/\Delta V$ versus ΔV; gas: O_2; $V_2 = -10$ kV.

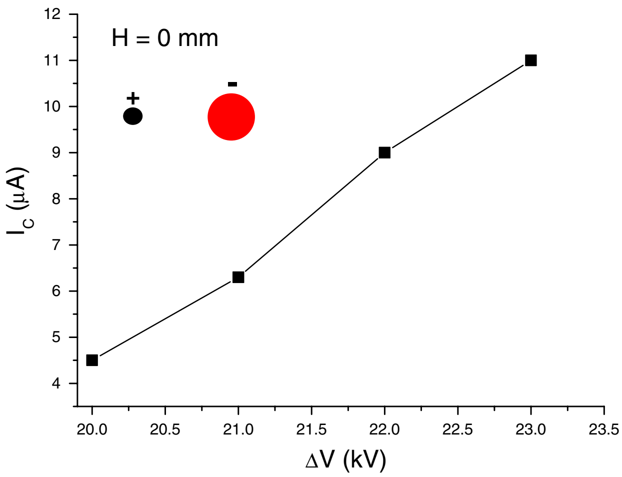

Figure 6. I_C versus ΔV for $H = 0$; gas: N_2; $V_1 = -10$ kV.

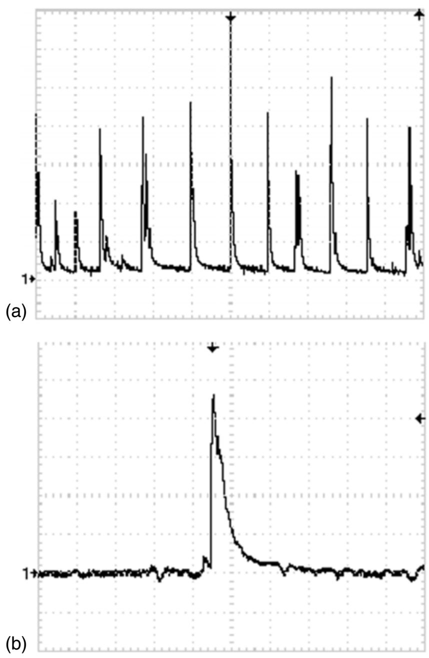

Figure 7. (*a*) Typical current signal for the plasma sheet regime; $\Delta V = 26$ kV; gas: dry air; $H = 0$ mm; $V_2 = -10$ kV; current scale 100 μA/div (arrow 1 indicates zero current); time scale 2.5 ms/div; $I_C = 50\,\mu$A. (*b*) Typical ac current signal for the plasma sheet regime; $\Delta V = 26$ kV; gas: dry air; $H = 0$ mm; $V_2 = -10$ kV; current scale 200 μA/div; time scale 2.5 μs/div; trigger level 800 μA.

This quadratic dependence of currents with electrode voltage is characteristic of unipolar coronas with space charge limitation. V_o is associated with the threshold of self-sustaining discharge and $\boldsymbol{C}$ depends on ion mobility, pressure of the chamber and geometrical factors (Loeb 1965, Sigmond 1982).

The slope of this fitting was rather uniform for different H values. However, the curves deviate from this prediction for the high voltage values, corresponding to a situation characterized by bipolar conduction phenomena. The adjustment with this kind of function for the case $H = 0$ in air seems quite good in all the range of voltages of appearance of the plasma sheet. This curve, however, does not share the same fitting curve than for the others, H.

When using pure nitrogen as the working gas, no stable bipolar corona could be established when $H > 0$ for the investigated range of voltage values. However when $H = 0$ and only when the small wire was positive a plasma sheet configuration could be observed. This regime appeared for a reduced range of voltages with dc current versus voltage characteristic as shown in figure 6.

In figures 7(*a*) and (*b*) typical signals of the current for the plasma sheet regime are presented. It can be seen that current peaks were superposed to a dc component (I_C) of relativly small amplitude compared with the peak height. The peak width at half-height is approximately 1.5 μs. The peak repetition rate (f_r) as a function of the maximum pulse height for different values of the electrodes voltage are presented in figure 8. It can be seen that for larger voltage drops peaks of higher values appeared and at the same time the frequencies of repetition of the different peaks were more uniformly distributed. In figure 9 a comparison between the f_r values obtained with N_2 and dry air in the sheet regime is presented. It can be seen that the pulse frequencies obtained with N_2 are around one order of magnitude smaller than those obtained with dry air.

In figure 10 a comparison between the averaged pulsed current (I_P) and I_C components in the sheet regime is presented. The I_p values were obtained by integration considering the peak distribution. The total averaged current I_T is obtained by adding the pulsed and dc components. Two sheet images are included in the figures for different ΔV values, to show that a more uniform distribution of luminosity was obtained at the higher voltages. As can be seen the contribution of I_p to I_T is always lower than the contribution of I_C.

3.2. *Momentum transfer to neutral particles*

The flow direction was always from the small wire to the larger one, but much more reproducible results were obtained for the positive small wire case. A similar behaviour can also be observed with unipolar coronas in a point-to-plate arrangement, where the induced wind is always directed from the point to the plate independently of the polarity of the point (Goldman and Sigmond 1982). The measurements of the flow velocity (v_g) obtained from the pressure probes at different H values for a positive small wire can be seen in figure 11 for air and O_2 gases. This velocity was in the range of 0.4–3.4 m s^{-1} and was a function of the discharge current. The higher values of velocities were observed when the higher currents were flowing in the system.

Different authors (Robinson 1961, Ballereau 1980, Sigmond and Lagstad 1993, Owsenek *et al* 1995) proposed a scaling law of the type $v_g = \sqrt{i}$ or equivalently $v_g^2 = i$ for devices with point-to-plane arrangements. This expression was obtained considering the momentum conservation equation of neutral particles, forced by ion impact, for a steady and parallel flow developing in the current flow direction.

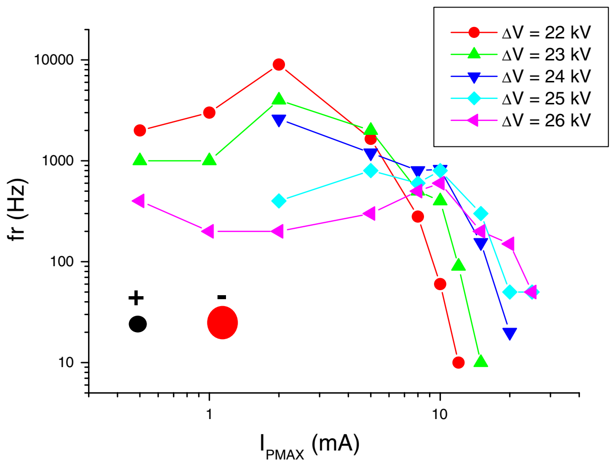

Figure 8. Pulse frequency (fr) in the plasma sheet regime versus I_{PMAX} (maximum peak height); gas: dry air; $H = 0$ mm; $V_2 = -10$ kV.

The above expression was deduced considering as negligible the friction effects and pressure gradients and that the electric force exerted on the ions is transferred to the gas molecules by elastic collisions, thus creating the electric wind.

Different researchers, like Bequin *et al* (2003), have recently proposed refinements to the original model obtained by Robinson, but the square root dependence was still obtained.

An adjustment with this kind of curve is represented in figures 12(*a*) and (*b*) where we observe that the velocity results scaled approximately with this law.

From figure 12(*a*) it can also be seen that in our experiments small increases in currents when the plate was close to the electrodes produced a larger increase in velocities than when the plate was away.

The induced velocities were in general higher when the plate was placed at larger distances from the electrodes. However, in the $H = 0$ case a lower induced wind on the stagnant fluid does not necessarily represent a lower fluid-discharge interaction. The decrease in the induced wind intensity as H decreases could have originated, for instance, from an increase in the effect of friction with the plate.

On the other hand, it should be taken into account that the induced velocity intensity does not necessarily give a measure of the actuator performance, since in a real situation the actuator must exert a forcing within a boundary layer.

In this situation an electromechanical coupling different from momentum transfer (like modifications of mechanical properties of the fluid) could also occur. In this sense, the large ionized regions produced in the close vicinity of the wall by the plasma sheet regime may promote fluid-discharge interactions quite different from those of other kinds of actuators.

A description of this complex interaction is beyond the scope of this paper as it requires the formulation of a discharge model supported by data issued from other complementary physical measurements).

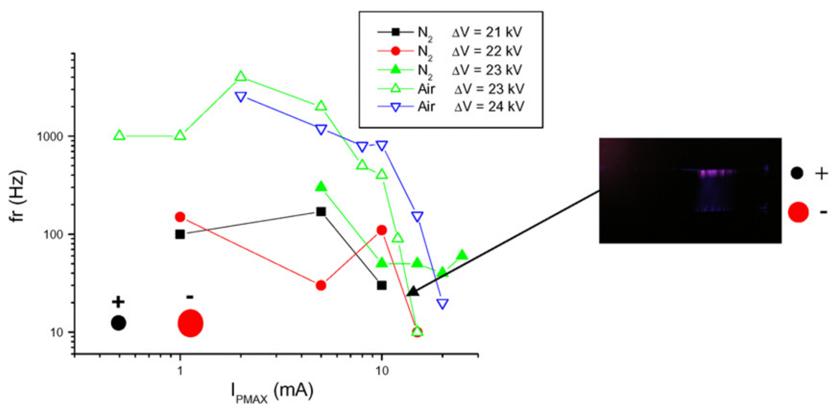

Figure 9. Comparison of the pulse frequency (fr) in the plasma sheet regime for N_2 and dry air; I_{PMAX}: maximum peak height; $H = 0$ mm; $V_2 = -10$ kV.

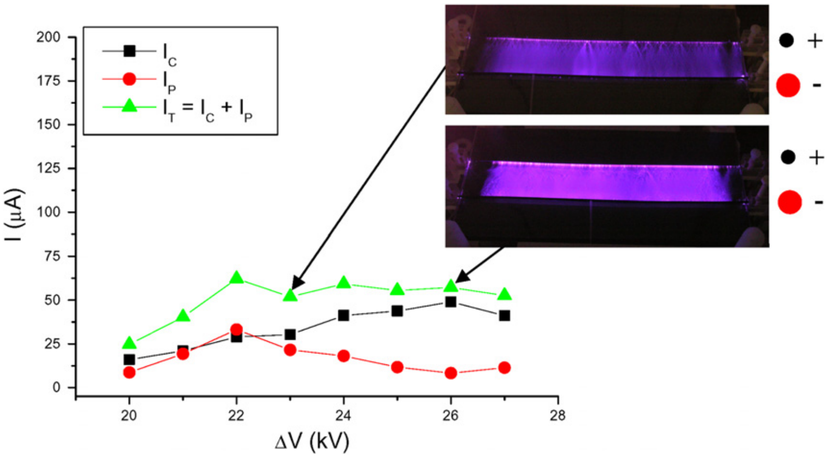

Figure 10. I_C (dc current), I_P (average pulsed current) and $I_T = I_P + I_C$ versus ΔV; gas: dry air; $H = 0$ mm; $V_2 = -10$ kV.

4. Discussion

The bipolar conduction character of the wire-to-wire configuration becomes evident considering the light emission at both electrodes and the unsuitability to fit the curve with the quadratic law proposed by Loeb at large ΔV values.

The dc component seems to be produced by a relativiy small number of electrons which originated in the ionization region of the negative corona that drifts towards the positive electrode (some of them being free of attachment) and are amplified in the ionization region of the positive corona. This explanation is suggested by the behaviour of the discharge characteristics curves (figures 3 and 4) which show first a smooth increase in the current at the low voltage range (unipolar behaviour) followed by a sudden increase associated with a strong electron multiplication in the ionization region of the positive wire.

The proximity of the plate reduces notably the dc current, a phenomenon that could be associated either with the electron capture by the surface that decreases the number of electrons drifting in the inter-electrode space or with considerable distortions of the electric field in the interelectrode space.

This behaviour is present at $H > 0$; however the case of $H = 0$ deserves a deeper analysis because it is the one where plasma sheet regimes may take place. In the plasma sheet regime peaks are combined with a glow that produces the dc current. Even though the contact of the electrodes with the surface could allow a conduction current through the dielectric material, the values of the surface resistivity of the Mylar ($2 \times 10^{10}\,\Omega$) are high enough to disregard this effect and the dc current can in fact be attributed to a gas volume discharge. The results of figure 5(*a*) indicate that this dc current is poorly influenced by the presence of peaks.

Based on the studies of coronas discharges and on the fact that both electrodes present ionization regions the pulses that appeared in this regime may be associated with different phenomena: negative streamers (anode directed); positive glow oscillations; Trichel pulses; positive streamers (cathode directed).

The negative streamers condition $Ne > 10^6$–10^8 (where Ne is the electron number at the streamer head) and large high fields required (in air $\sim$1.8 MV m^{-1}) for stable propagation are conditions that in general are not found in coronas (Goldman and Sigmomd 1982, Loeb 1965). So in principle this mechanism should be regarded as quite improbable to originate the pulses. This consideration can be reinforced by the visual

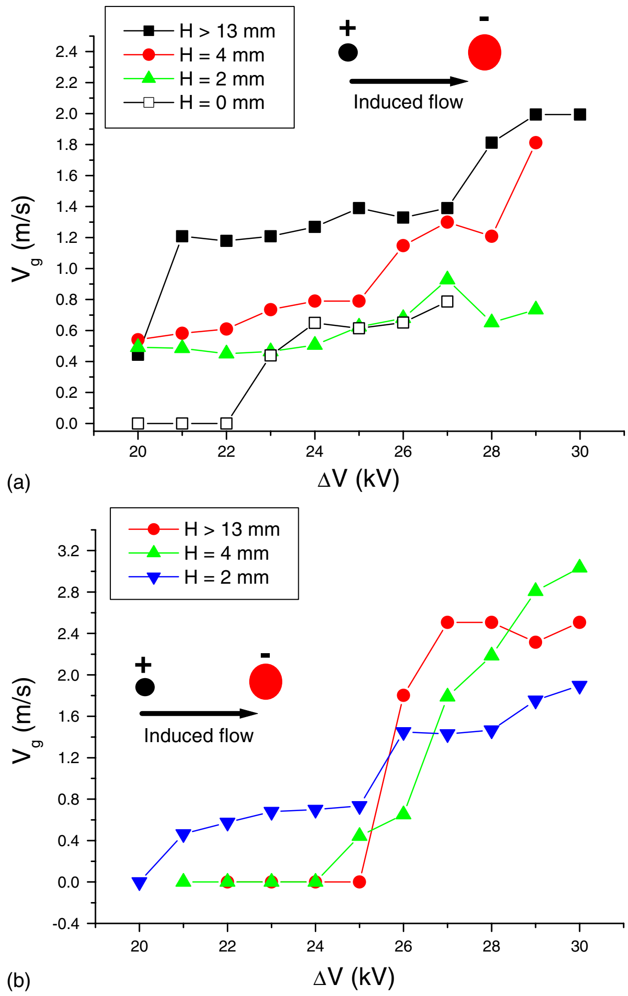

Figure 11. (*a*) Flow velocities induced by the gas discharge (v_g); gas: dry air; $V_2 = -10$ kV. (*b*) Flow velocities induced by the gas discharge (v_g); gas: O_2; $V_2 = -10$ kV.

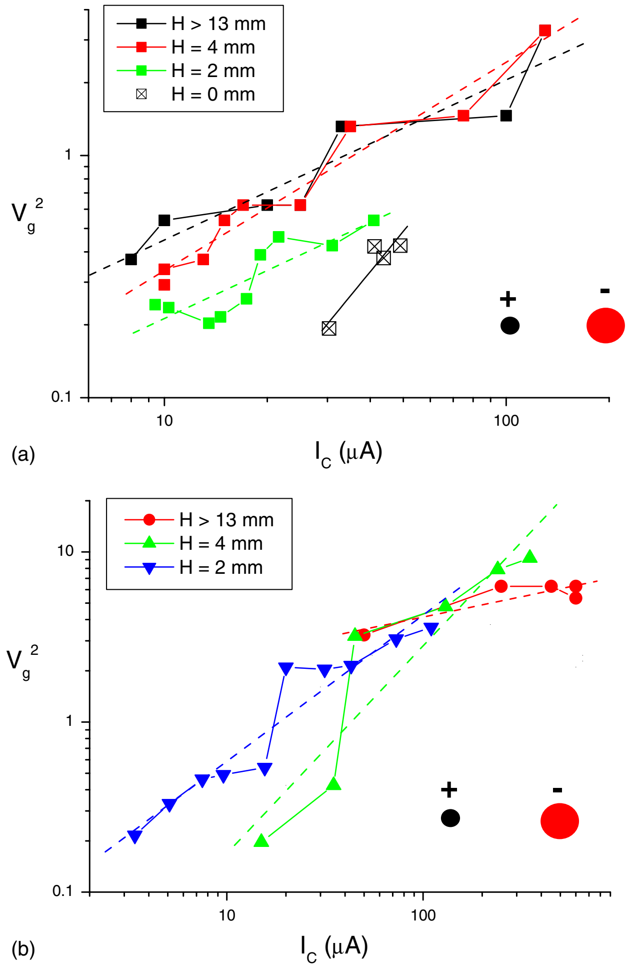

Figure 12. (*a*) v_g^2 versus I_C; gas: dry air; $V_2 = -10$ kV. (*b*) v_g^2 versus I_C; gas: O_2; $V_2 = -10$ kV.

inspection of the plasma sheet discharge that looks always like a diverging plume of several filaments with its vertex on the anode. In general these filaments reached the cathode but may also stop and disappear at mid-gap positions. Also the fact that the plasma sheet was not observed when the cathode was the small wire indicates that the negative streamer hypothesis is rather improbable.

Positive glow oscillations seem also quite improbable in our case as this kind of oscillations have very large frequencies (MHz) not comparable with the kHz frequencies observed in our case.

So this kind of pulse should be ascribed either to Trichel pulses or positive streamer formation. The analysis of the shape and duration of the pulses when the electrodes were placed in contact with the surface ($H = 0$) does not enable one to conclude if the pulses are directly associated with streamers or to Trichel pulses as both have similar rise time and duration (Sigmond and Goldman 1983). However, Trichel pulse shape is independent of the corona average current while streamers are always associated with current pulses with voltage dependent frequency. As we can observe from figure 8 the last situation is produced in our study. Other elements like the cracking noise that can be heard during the experiment or the large ozone production reinforces this concept. On the other hand the presence of an insulating surface has revealed it to be a method to control and eliminate Trichel pulses more than to promote its appearance as was observed in our experiments (Akishev *et al* 2005).

Concerning the influence of the surface material and the gas composition on the plasma sheet establishment, it should be noted that the plasma sheet formation depends on the gas composition, surface characteristics and gap geometry. We have concentrated our analysis on the first two variables.

It is expected that the formation of positive streamers along a surface depends on the same parameters that are present in bulk discharges (gas type, electrode geometry, electrode voltage, etc) and on those associated with the surface presence.

The energy threshold for photo-ionization of the gas seems to be a crucial value in promoting the propagation of streamers along the surface. This assertion is based on the fact that the cross section of photo-ionization of N_2 (26×10^{-22} m^2) is much larger than the cross section of O_2 (1×10^{-22} m^2, see Raizer 1991) and the plasma sheet is obtained with N_2 and air and not with O_2. Another evidence that the photo-ionization is an important mechanism for electron generation is that the transition from the streamer-like discharge to a spark is achieved at a lower voltage for N_2 ($\Delta V \geqslant 23$ kV) than for air ($\Delta V \geqslant 27$ kV).

The limited voltage forming conditions for the N_2 plasma sheet are associated with the voltage range studied in this experiment ($\Delta V = 20$–30 kV). It is expected that for a lower voltage a stable plasma sheet configuration could be obtained for N_2, leading to a voltage range similar to that found for air, but shifted in the N_2 case to lower voltage values.

The influence of the surface in the discharge may appear through alterations of the local electric field associated with the polarization of the surface or to the charge deposited on the surface (Akyuz *et al* 2001). The dielectric surface may also alter the phenomena of streamer propagation not only through the presence of the above quoted surface charges, but also as it may constitute a source of photo-electrons acting in the close vicinity of the head of the streamer (photo-emission limit of the dielectric $\sim$4 eV $<$ photo-ionization limit of the air $\sim$12 eV). Even though these surface effects promote the formation of streamers, our oxygen results indicate that it required a complex coupling with the gas particles to promote the streamer propagation.

From figure 11(*a*) (case $H = 0$), it can be seen that a sudden increase in the flow velocity appears as the streamer (sheet) regime is established ($\Delta V \geqslant 22$ kV). The expression that quantifies the momentum transfer in electrically non neutral regions could be extended to describe the forces appearing on the neutrals due to the presence of streamers. In this case, the momentum transfer is very likely produced during the decay phase of the streamer, when the remaining ions (mostly positive) spread into the inter-electrode gap.

5. Conclusions

We have studied a two-wire asymmetrical (different diameters, opposite polarity) electrode configuration in the presence of a dielectric plate and under different gases. For large distances wire-plate it has been found that the discharge current consists of a purely dc component, even though both electrodes remain active for a large range of applied voltages. The proximity of the plate reduces notably this dc current component, until in the limit situation for which the electrodes practically lay on the plate a current pulsed regime is superimposed to the dc (small) component, thus establishing a plasma sheet regime. This regime could only be reached, with the small wire positive, for a broad range of voltages in the case of using dry air as the working gas. With nitrogen gas the plasma sheet regime was established only for a very limited range of voltages (before sparking) and with oxygen gas the regime was never reached. The pulses in the current exhibit a characteristic duration of about 1.5 μs and typical frequencies of about 1 kHz. For the larger voltage drops of our study, peaks of higher values appeared and at the same time the frequencies of repetition of the different peaks were more uniformly distributed.

The pulsed regime may be identified with a succession of positive streamers (cathode directed) while the dc component seems to be produced by a small number of electrons which originated in the ionization region of the negative corona that drifts towards the positive electrode (some of them being free of attachment) and are amplified in the ionization region of the positive corona.

Different parameters of the gas and surface characteristics (thresholds of photo-ionization and photo-emission, charge deposition, etc) promote the streamer propagation.

By studying the induced electric wind, it seems that these streamers of the sheet regime can contribute appreciably to the ion momentum transfer of the gas. This transfer should be due very likely to the drift of the charged species present in the streamer channel during the streamer-collapsing phase. The source of momentum transfer associated with the dc current would always persist with a magnitude that depends on the intensity of this current.

A final consideration is related to the possibility of other electromechanical coupling mechanisms between discharge and airflow, associated with the plasma sheet. In this research we have limited our analysis to the momentum transfer mechanism by ion collision. It should be borne in mind, however, that when the densities of charged species are high enough the alteration of physical properties of the gas-plasma system (density, viscosity, etc) in the adjacency of the surface of the body could be relevant. In view of our results this mechanism is worth being studied since the streamers have associated larger ion densities than those of the drift region of unipolar coronas.

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