Surface corona discharge along an insulating flat plate in air applied to electrohydrodynamically airflow control : electrical properties

E Moreau [(1)], G Artana [(2)], G Touchard [(1)]

[(1)] Laboratoire d'Etudes Aérodynamiques, UMR 6609 CNRS, Electrohydrodynamic group, Université de Poitiers, Téléport 2, Bd Curie, BP 30179, 86962 Futuroscope, France.
[(2)] Universidad de Buenos Aires, Facultad de Ingeniería, Paseo Colón 850, 1063 Buenos Aires, Argentina.

Abstract. Several studies have shown that a surface corona discharge may be used as an air-moving actuator in order to control the airflow around an obstacle, such as an airfoil to enhance lift or to reduce the drag for example. For few years, our laboratory has been working on this subject, especially in the case of a DC corona discharge. Although efficient aerodynamic effects have been observed, it is sometimes difficult to control the discharge properties. Consequently, the present paper deals with an experimental work about the electrical properties of a DC surface corona discharge established between two wire electrodes flush mounted on the wall of a PMMA insulating plate. This study shows that (1) Several discharge regimes may be obtained as a function of the applied electric field. (2) When the free airstream flows in the same direction of the ionic wind, the discharge is more stable and its current increases with the airstream velocity U_0. (3) When the gas flows in the opposite direction ($U_0 < 0$), the current is quite stable. (4) The discharge current is nearly proportional to E/P where E is the electric field and P the gas pressure. (5) Higher discharge currents may be reached when the negative polarity is applied to the wire electrode with the upper diameter. (6) The discharge current decreases when the air humidity RH increases. (7) In a range between +20°C and +65°C, the wall temperature has no influence on the discharge. (8) To obtain a more stable DC corona discharge, one needs U_0 high, RH low and the positive polarity must be applied to the wire electrode with the lower diameter.

1. Introduction

When a high potential difference between two electrodes is applied, ions are produced and drift from the injection electrode to the collecting one under Colombian forces. They exchange momentum with the neutral fluid particles and induce a fluid motion usually called ionic wind. In the case of a corona discharge established in ambient air between two wire electrodes flush mounted on the surface of an insulating material, we have previously proposed that positive ions were produced at the anode and electrons at the cathode [1-2]. Indeed, very few negative ions are produced at the cathode, and they may be neglected. Under Coulombian forces, these charges drift to the electrode of opposite sign. Because the electron mass is negligeable compared to the ion mass, the ionic wind is mainly due to the positive ion drift, from the anode to the cathode (Figure 1). For few years, we have been studying the ability of using this type of actuator to control airflow along the wall of an obstacle. This is *electroaerodynamical control*. The goal of this electrohydrodynamic actuator is to modify the airflow profile within the boundary layer. The main advantage of this process is that it directly converts electric energy into kinetic energy, without any moving mechanical part. This process might be used by aeronautic industry to reduce the drag of a plane or to stabilize the flow in order to avoid unsteadiness which generate unwanted vibrations, noise and losses.

In previous works [1-5], a great number of experiments such as visualizations, particle imaging velocimetry (PIV) measurements, velocity profile and wall pressure measurements with different types of obstacles (flat plates, circular cylinders, NACA airfoils) for velocities up to 30 m/s with associated Re number up to 10^5, allowed us to show a high acceleration of the airflow downstream the discharge when the ionic wind acts in the direction of the free airstream. Indeed, the ionic wind induced by the corona discharge increases the velocity at close vicinity of the wall, resulting in many cases in an airflow reattachment (Figure 2) or reduction of the wake size. Although this process is very promising, the main inconvenient of the DC discharge is that its properties depend highly on the atmospheric conditions of the ambient air and the electrode geometry. Consequently, the purpose of the present paper is to study the surface corona discharge as a function of several parameters in order to enhance its stability. More especially, we will observe the influence of several parameters on the discharge properties. These parameters are the free airstream velocity, the air pressure, the electrode polarity, the wall temperature and the air humidity.

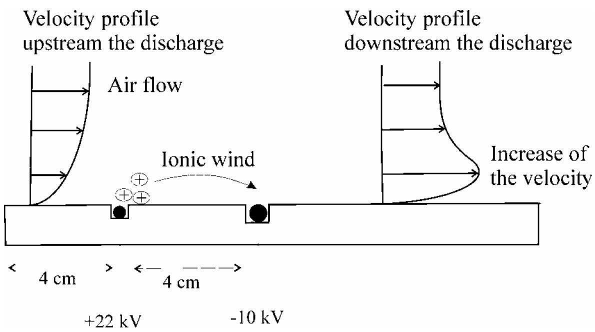

Figure 1. Schematic representation of the electrohydrodynamic actuator.

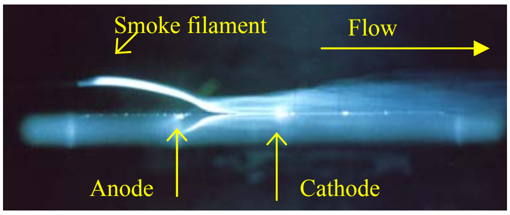

Figure 2. Visualisation of an airflow along a flat plate turned off toward the wall by a DC discharge.

2. Experimental setup

The obstacle is a flat plate in PMMA. Its thickness is 4 mm. The anode is a 0.7-mm diameter copper wire electrode placed inside a 0.7-mm depth groove at 4 cm downstream the leading edge. The cathode is a 2 mm diameter wire placed inside a 2 mm depth groove, 4 cm downstream the anode (Figure 1). Electrode length is 22 cm. The DC surface corona discharge is obtained by application of a high positive potential at the anode (≈ + 22 kV) and a negative potential of -10 kV at the cathode. Two DC HV power supplies DELL (± 40 kV, 3.75 mA) are used. In previous works, the wire cathode was sometimes replaced by a plate such as a aluminium foil [4-5].

The wall temperature may be controlled by a flat filament resistance of 150 Watt sticked on the rear side of the flat plate. A temperature sensor (accuracy 0.1°C) is placed on the side where the discharge is established. The potential difference and the mean value of the discharge current are indicated by the HV power supplies DELL with a precision of 0.1 kV and 10 µA respectively. More, the alternating component of the discharge current may be visualised with the help of a AC current transformer (ACCT Bergoz, current full scale 1 mA, precision lower than 3 µA, bandwidth of 300 kHz) connected to a TREK oscilloscope. The current transformer consists of a toroid sensor with inner diameter of 28 mm placed around the positive HV cable. To modify the free air stream velocity U_0, the flat plate is placed in a wind tunnel loop (U_0 up to about 30 m/s). The incidence angle of the obstacle is adjustable and the obstacle direction may be changed. The velocity U_0 is measured with a Pitot tube connected to a micromanoter. Precision is typically 0.025 m/s. Furthermore, discharge experiments may be performed in a chamber where the pressure P is adjustable in a large range ($10^2 < P < 10^5$ Pa).

3. Electrical properties

3.1. DC Discharge at ambient conditions

To establish the surface corona discharge, a negative potential of -10 kV is applied at the cathode, and an adjustable positive potential is applied at the anode. Then in ambient air, positive ions are created at the anode and drift to the cathode with a mean velocity depending on their mobility. Figure 4 shows the discharge current per unit length I (mA/m) as a function of the applied electric field E (kV/cm). The current per unit length is the ratio of the discharge current with the electrode length. (v.g., a discharge current of 100 µA with 22 cm length electrodes corresponds to $I \approx 0.45$ mA/m). In Figure 4, one can see that the current increases with $E=V/d$, V being the voltage difference between electrodes and d the distance separating them. When the electric field between both electrodes increases, several discharge regimes may be observed. They have been accurately described in [2]. The range of these different regimes may highly vary as a function of geometric parameters (such as the position of the electrodes, the distance between the electrodes, the shape of the electrodes, etc.) or atmospheric parameters (such as ambient air humidity, pressure, etc…). In the experimental conditions used here (air humidity between 45 % and 55 %), the followings results are obtained: above the corona-starting voltage (5.25 kV/cm in Figure 4), the first regime is the "spot type" regime. The discharge is then concentrated in some visible spots on the wire. The current density is smaller than 0.3 mA/m and the ionic wind is low. When the electric field is increased, a thin sheet of blue ionized air between the two electrodes may be observed (current values from 0.3 to 0.8 mA/m). For higher currents (from 0.8 to several mA/m), the "high spot type" discharge is obtained. With the high spot type discharge, one cannot observe a thin sheet of blue ionized air between the two electrodes. Compared to the generalized glow discharge, the two main advantages of the high spot type discharge are its stability and the fact that high current values (and then faster ionic winds [3]) may be reached. If the electric field increases more, the whole current is concentrated in some filaments; this is the "filamentary type regime". Above, sparks appear and the discharge is very difficult to control. Figure 5 presents a typical discharge current as a function of time for a mean current of 300 µA ($I \approx 1.4$ mA/m and $E \approx 8.6$ kV/cm). It shows that there are lots of current peaks with a magnitude up to 40 µA and a response time τ from 20 µs to 100 µs. A FFT analysis indicates that the most part of these current peaks have a frequency lower than 10 kHz.

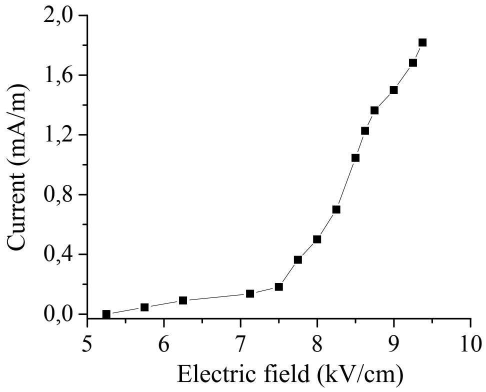

Figure 4. Current versus electric field.

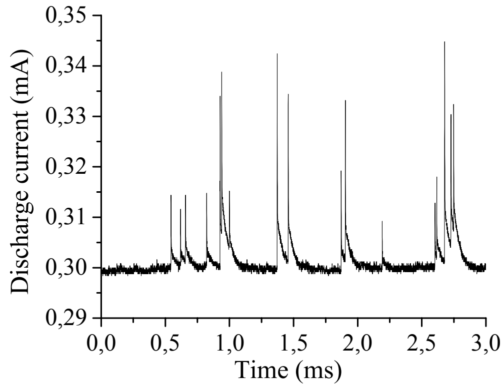

Figure 5. Discharge current versus time (U_0=0 m/s and E = 7.6 kV/cm).

3.2. Influence of the free air stream velocity U_0

The local current density in ith direction J_i depends on the local magnitudes of the free charge density ρ_c, the ion diffusion coefficient D, the ion mobility μ, the electric field E_i and the convective velocity u_i in ith direction. It may be expressed as:

$$J_i = D\frac{\partial \rho_c}{\partial x_i} + \rho_c\left(\mu E_i + u_i\right) \qquad (1)$$

In classical electrohydrodynamical theory, the diffusive and convective terms are usually neglected. This simplification is justified because these terms are largely lesser than the coulombian drift term. However in aeronautic applications, convective velocity is high and it can not be neglected. For instance, in our experiments and considering the ion mobility $\mu \approx 2.0\ 10^{-4}$ m^2/Vs, the coulombian drift velocity μE_i is about 150 m/s while u_i is comparable to $U_0 \approx 30$ m/s. Figure 6 presents typical curves of current versus electric field for U_0 equal to 0 and 30 m/s. It shows that the discharge current and the corona starting voltage increases with U_0. In Figure 7, in the case of the square symbols, the electric field E is fixed at 7.5 kV/cm, U_0 at 0 m/s and the current is about 0.4 mA/m. Then if one increases U_0 we can observe that the discharge current increases almost linearly with the free air stream velocity as predicted by Eq. (1). More, below 12 m/s the discharge is “high spot” while above 12 m/s it becomes “glow”. This means that the airflow favoures the “glow discharge” in spite of the “high spot” type discharge. Same behaviors are obtained with E equal to 8 and 8.25 kV/cm. In order to increase the convective term u_i, we have inclined down the leading edge of the plate to an incidence angle α of 10 degrees. As in Figure 6, Figure 8 presents the current-electric field characteristics for different U_0 values. It shows that the slope of the E-I characteristic increases with U_0. Taking into account Eq. 1 and if we consider that the cross-section area of the discharge is constant, then the slope of these characteristics is $\rho_c \times \mu$. Then the slope increase may be associated to an increase of the space charge density ρ_c with U_0.

Figure 9 presents the current as a function of the free airstream velocity for α equal to 0 and 10 degrees and E = 8 kV/cm. As previously indicated by Figure 7 for α = 0, it shows that the discharge current increases with U_0. The effect is higher when the plate is inclined because the convective term u_i is higher. On the other hand, if the air stream flows in the opposite direction of the current, the convective term u_i of Eq. 1 should diminish the current value because it is negative. However when the flat plate is reversed in the wind tunnel loop, the current does not decrease but increases slightly. This result shows that the influence of the air flow is not restricted to the convective effect. It indicates that the phenomena of charge generation, charge distribution, charge drift and convection are strongly coupled. Figure 10 presents the alternative component of i (t) at 30 m/s for $\alpha = 10°$. Compared to Figure 5, Figure 10 shows that the airflow largely increases the peak repetition and modifies the discharge spectra. This confirms that the airflow modifies considerably the discharge.

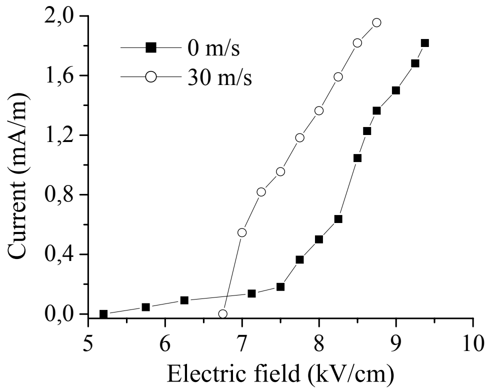

Figure 6. Current versus electric field for 2 air stream velocity values.

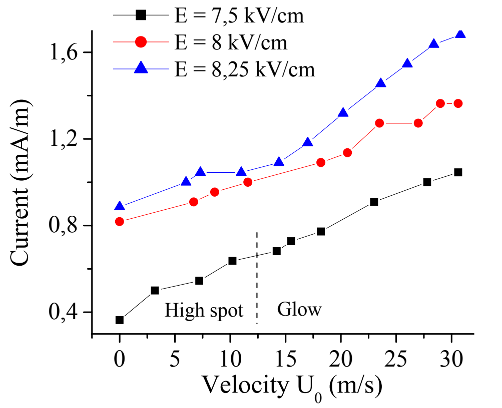

Figure 7. Current versus air stream velocity for 3 electric field values.

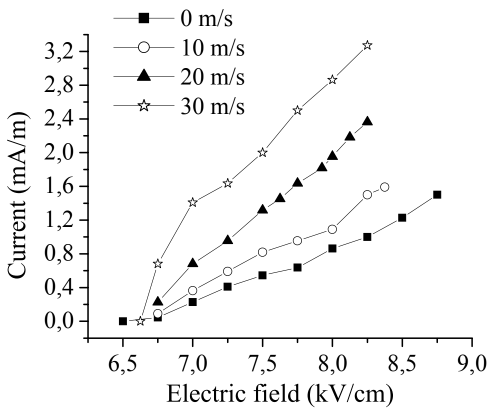

Figure 8. Current versus electric field for 4 airstream velocities with $\alpha = 10°$.

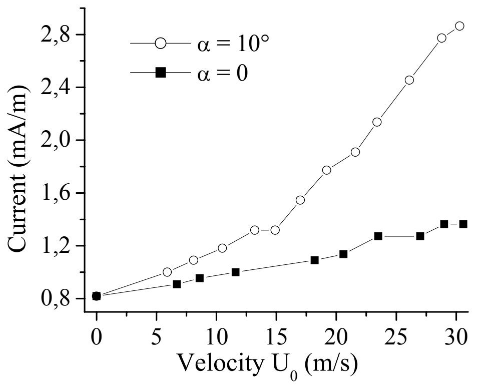

Figure 9. Current versus free air stream velocity for E = 8 kV/cm.

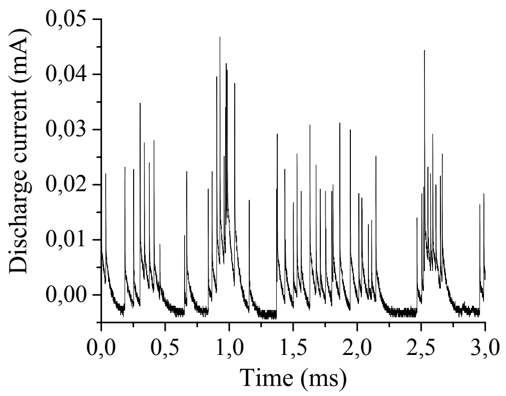

Figure 10. Alternating component of the current ($I_{mean} \approx 300\ \mu A$) versus time for $U_0 = 30$ m/s and $\alpha = 10°$.

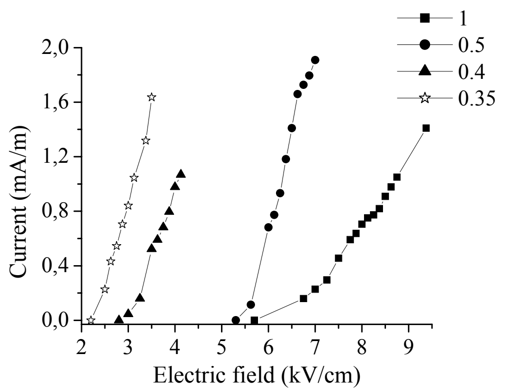

Figure 11. Current versus electric field for different air pressure values (in 10^5 Pa).

3.3. Influence of the air pressure P

One parameter which may change in aeronautic applications for example is gas pressure. It is the reason why we studied the discharge behaviour in a large range of pressures ($10^2 < P < 10^5$ Pa). For instance, Figure 11 presents the current-electric field characteristics for different pressure values. It shows that the discharge needs a lower electric field when the pressure decreases. In fact, as previously observed in the case of a AC discharge [6], it seems that the current is nearly proportional to E/P. On one hand, when decreasing the pressure until 10^4 Pa, the discharge becomes more and more stable and homogeneous. On the other hand, when the pressure is lower than 10^4 Pa, the discharge is more and more concentrated in some visible points on the electrodes such as a filamentary discharge. It is then difficult to obtain a homogeneous discharge along the surface of the insulating plate.

3.4. Influence of the electrode polarity, the plate temperature and the air humidity

Others parameters have been studied. Briefly, results are followings: (1) Concerning the influence of the electrode polarity on the ionic wind velocity, results will be published very soon. Meanwhile, as in cylindrical configuration [7], the present study has shown that higher discharge currents (about +20 to +50 %) were reached when the negative polarity was applied to the wire electrode with the lower diameter (+10 kV at the 2 mm diameter electrode and ≈ - 20 kV at the 0.7 mm diameter electrode). This behaviour has been observed whatever the air pressure. (2) In a range between +20°C to + 65°C, the wall temperature has no influence on the discharge properties. (3) In the case of a PMMA flat plate, the discharge becomes unstable when the air humidity is higher than 55 %. Below this threshold, the discharge current decreases when the air humidity increases. More the air humidity promotes the "glow discharge" in spite of the "high spot type discharge". On the other hand, other behaviours may be observed with others insulating materials [8-9].

4. Conclusion

This experimental study has shown that the electrical properties of a DC surface corona discharge established between 2 flush mounted wire electrodes depend highly on the air properties, such as its pressure, its velocity and its humidity. In order to obtain a more stable discharge, one needs a pressure between 10^4 and 10^5 Pa, a low humidity (RH < 50 %) and a high air stream velocity (up to 30 m/s in our case).

References

[1] Léger L, Moreau E, Artana G, Touchard G 2001 *J.of Electrostatics* **50-51** 448-454

[2] Léger L, Moreau E and Touchard G 2002 *IEEE Trans.on Ind. Appl.* **38** 1478-1485

[3] Léger L, Moreau E and Touchard G 2002 *1st AIAA Flow Control Conf. paper #2833*

[4] Artana G, D'Adamo J, Moreau E, Touchard G 2002 *AIAA Journal* **40** 1773-1779

[5] Artana G, Diprimio G, Desimone G, Moreau E, Touchard G 2001 4th *AIAA Weakly ionized Gases Conf., paper #3056*

[6] Moreau E, Léger L and Touchard G 2002 *IEEE – CEIDP* 272-278

[7] Artana G, Desimone G and Touchard G 1999 *Electrostatics Cambridge* 147-152

[8] Louste C, Moreau E and Touchard G 2003 *Electrostatics Edimburg*

[9] Louste C, Moreau E and Touchard G 2002 *IEEE – CEIDP 822-826*