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# **A DC corona discharge on a flat plate to induce air movement**

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## **Abstract**

This paper describes a DC surface corona discharge designed to modify the airflow around a flat plate. The electrode configuration consisted of two thin copper layers placed on each side of the plate's attack edge. Discharge optical measurements with a photomultiplier tube indicated that the light emitted by the plasma is pulsating, at a frequency that increases with applied voltage. Moreover, with voltage higher than a threshold value, the electric discharge changes regime with brighter pulses. This discharge also induced an "ionic wind" whose velocity was measured with a pressure sensing probe (up to 1 m/s). Experiments with the Particle Image Velocimetry system in a subsonic wind tunnel showed that this discharge can reduce the separated airflow on the flat plate for a flow of 14 m/s (Reynolds number of 187,000).

*Keywords:* Corona Discharge; Electroaerodynamics; Ionic Wind; Plasma Actuator.

## 1. Introduction

The use of so-called ionic wind induced by a high voltage discharge [1] has been studied in electrostatic precipitators [2-3] and, more recently, in aerodynamics [4]. In this latter case, the ionic wind is used to modify the airflow around an obstacle in order to control the airflow in the boundary layer and reduce drag. For this purpose, different electric discharges have recently been developed, such as the “One Atmosphere Uniform Glow Discharge Plasma” [5-6] and DC surface corona discharges [7-9]. Labergue *et al.* [7] used the latter discharge on an inclined wall to detach the flow; Léger *et al.* [8] and Artana *et al.* [9] re-attached the flow on a flat plate. Published results indicate that the discharge can be used for active control of low velocity airflow, but the mechanism of interaction between discharge and flow has not yet been clarified.

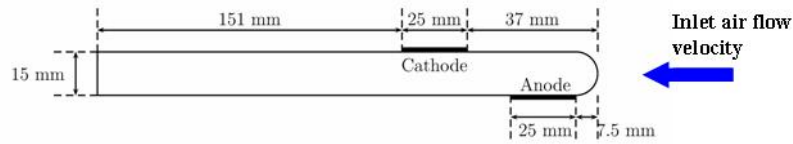
In this paper, we present an investigation of a DC corona discharge and measurements of the induced flow. The electrode configuration consisted of two metallic tapes placed on each side of a circular leading edge (see Fig. 1). This configuration slightly differs from that in reported works [8-9], where both wire electrodes were placed on the same side of the attack edge.

## 2. Experimental setup

### 2.1. Plasma actuator and power supply

The plasma actuator consisted of a DC surface-corona discharge established between two electrodes (copper, 170 mm long, 25 mm wide and 35

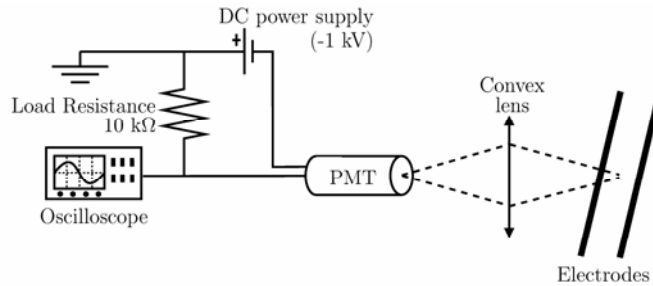
$\mu\text{m}$  thickness) mounted on both sides of the circular leading edge of a flat plate (PVC, polyvinyl chloride, 213 x 200 x 15 mm), as shown in Fig. 1. The anode was placed 7.5 mm downstream of the leading edge and connected to a positive high voltage source (SPELLMAN SL300, 0-60 kV, 5 mA); the cathode, placed 37 mm from the edge, was connected to ground. A 15-M $\Omega$  series resistor prevented the transition to an arc regime.



*Figure 1: DC surface corona discharge actuator on a flat plate.*

## 2.2. Optical Setup

As the light emitted by the discharge was very weak, a highly sensitive photomultiplier tube (Hamamatsu R928 having a spectral domain from 185 nm to 900 nm) was used to detect the plasma fluorescence. A load resistance of 10 k $\Omega$  was placed between the anode of the PMT and ground to measure the photocurrent. The rise time of the detection system was about 200 ns. The PMT signal was measured with an oscilloscope. The setup shown in Fig. 2 used a quartz lens to capture the ultraviolet (UV) light from the discharge.



*Figure 2: Optical setup for measurements using photomultiplier tube*

### 2.3. Wind tunnel

Experiments with external airflow were performed in a subsonic wind tunnel (Fig. 3) of 50 cm x 50 cm cross-section in a 2-m long test section (mean turbulence ratio of 0.5%), where a flow with maximum velocity of 50 m/s was generated by a 30-kW electric fan. The test flat plate was placed between two transparent rotating disks, shown in the test section in Fig. 3, which allow for obtaining the desired attack angle.

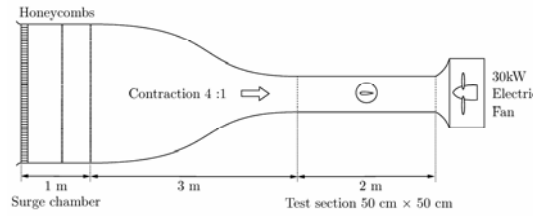


Figure 3: Schematic side view of the wind tunnel

### 2.4. Particle Image Velocimetry system

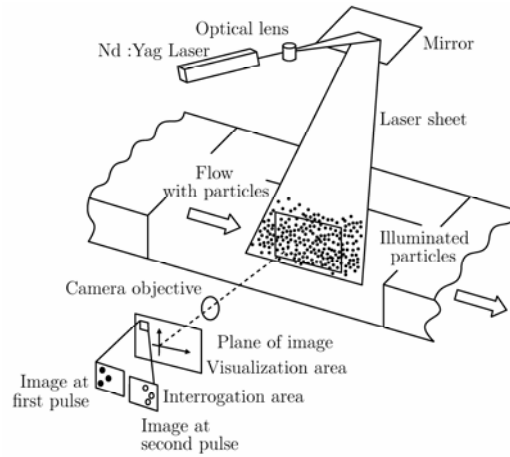


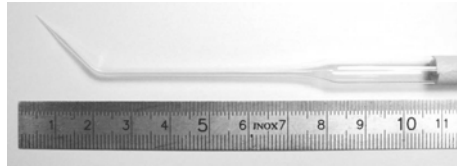
Figure 4: Experimental setup of the Particle Image Velocimetry system.

Measurements of the flow velocity fields were performed using the Particle Image Velocimetry (PIV) system shown in Fig. 4. A laser beam of wavelength 532 nm (Nd:Yag laser, Spectra Physics 400) was transformed into a laser light sheet using mirrors and lenses. The laser sheet illuminated smoke

particles (generated by incense sticks) which seeded the flow. Images of illuminated smoke particles were captured using a Charge Coupled Device (CCD) camera called PIVCAM. The vector displacement of each particle could be determined using two images recorded for two successive laser pulses having a time delay of 10  $\mu$ s. The velocity fields presented in this paper are the mean vector fields of 500 pairs of such images recorded over a duration of 50 seconds at repetition rate of 10 Hz.

### **2.5. Pressure sensing probe**

Velocity measurements were made with a pressure sensing probe consisting of a tube made of glass, shown in Fig. 5, thus avoiding conductive materials near the discharge that could cause unwanted arcs. The tube was connected to a differential low-pressure transducer Druck<sup>TM</sup> LPM 9481 (0-20 Pa, output voltage 0-5 V) and measurements were acquired on a PC using a 16-bit acquisition card, over a 2-s interval at a 2-kHz sampling rate. The flow velocity  $V$  was determined from the differential pressure values  $\Delta P$  using the Bernoulli relation  $\Delta P = \frac{1}{2} \rho V^2$ , where  $\rho$  is the air density. This sensor was calibrated with a classical Pitot tube in a calibration wind tunnel (DANTEC StreamLine 90H02 Flow Unit).

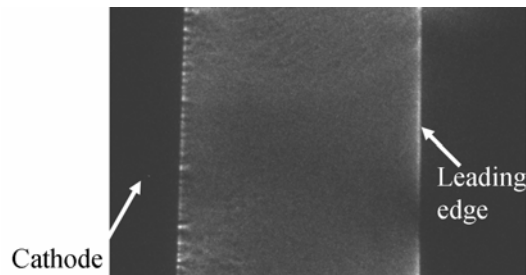


*Figure 5: Pressure sensing probe made of glass.*

## **3. Results and discussion**

### 3.1. Discharge characteristics

Using the configuration presented in Fig. 1, a stable discharge was obtained using a positive DC high voltage of 44 kV as shown by the photography in Fig. 6. The room's relative humidity was 44%. This photo was taken using an intensified CCD camera with a gating time of 1 second. The mean discharge current was 0.20 mA. The current per unit length of the electrode perpendicular to the edge was thus 1.2 mA/m. This value is approximately the same as that used by others authors [7-10].



*Figure 6: Photography of the discharge established on the flat plate.*

This apparent homogeneity in fact hides a much more complex time structure. Indeed, time resolved measurements using the PMT, shown in Fig. 7.a, reveal that the discharge is composed of a multitude of streamers at a repetition rate that depends on the working voltage. Notice that each negative peak of the PMT signal corresponds to a light pulse emitted by a streamer (called a “micro-discharge” in this paper in consideration of the low value of the corresponding measured intensity) mainly in UV range (because the light was strongly

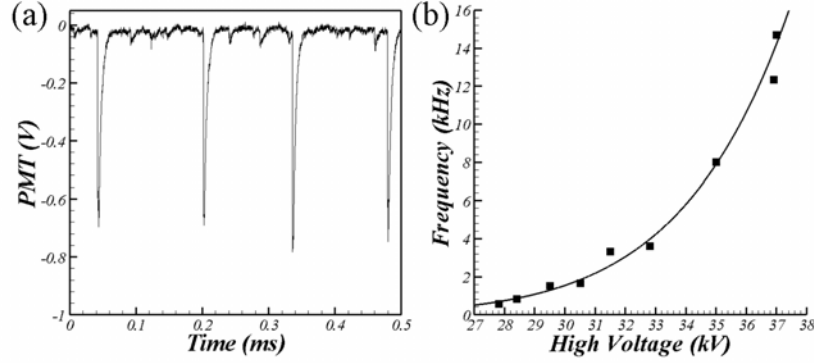


Figure 7: (a) Time evolution of corona discharges at 35 kV, and (b) frequency of the corona micro-discharges versus high voltage.

attenuated by glass non-transparent to UV). The frequency as a function of working voltage, up to 38 kV, is shown in Fig7.b. Despite the constancy of voltage, the corona discharge can be an intermittent one as shown by PMT measurement. This intermittence was discovered in Loeb's laboratory in 1938 [11]. In case of a negative corona, the pulses are called Trichel pulses and its frequency is much higher than the one of positive corona used in this experiment [12].

In our specific setup, the discharge regime changed when the working voltage was higher than 38.5 kV. Indeed, the appearance of the discharge became much more luminous and visible to the naked eye. The PMT signal, in Fig. 8, showed the appearance of some stronger discharges (called macro-discharges in this paper). Each macro-discharge caused a voltage drop as shown by the second curve in Fig. 8.

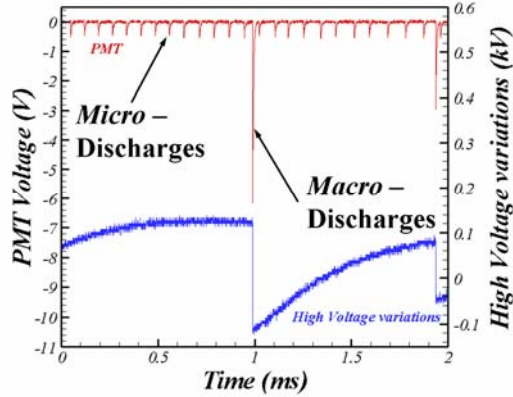


Figure 8: Time evolution of corona discharges and high voltage variations at 39 kV.

### 3.2. Induced flow velocity

In an initially still atmosphere, the DC surface corona discharge induces airflow (called ionic wind) due to the movement of positive ions from anode to cathode. Usually, plasma is composed mainly of electron and positive ions. However, due to the electron attachment, plasma created in air also contains negative ions of oxygen. But the effect of these negative ions is less important than the effect of positive ions because the induced airflow is always from anode to cathode in the case of a positive working voltage [10]. This weak contribution of negative ions is probably due to a lower concentration of these ions.

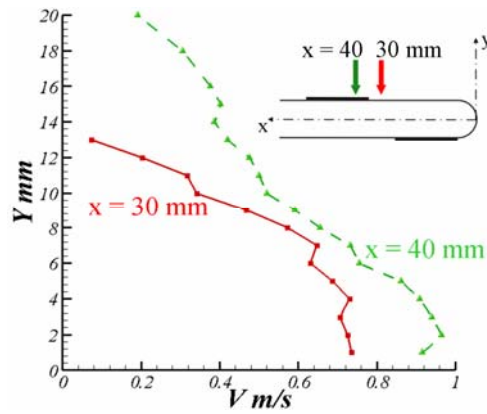


Figure 9: Ionic wind velocity profiles at different positions (44 kV).

The induced flow velocity profiles at two positions were measured and results are given in Fig. 9 for a working voltage of 44 kV. The maximum of the time-averaged velocity values, obtained above the cathode, was about 1 m/s.

### 3.3. Airflow modification by plasma

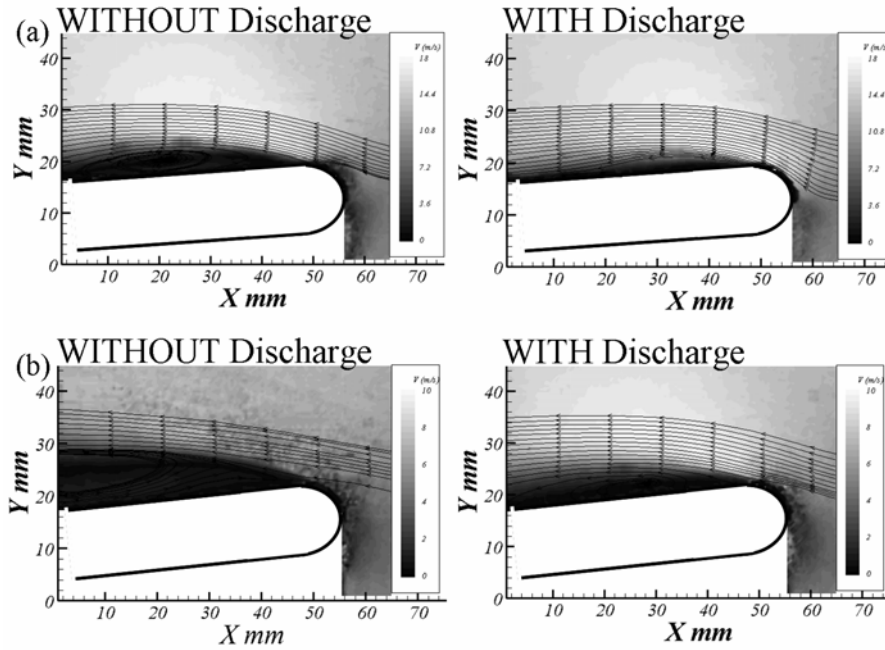


Figure 10: Time averaged velocity fields with and without discharge (40 kV, 0.8 mA/m) (a) for an angle of attack of  $2.5^\circ$ , and an inlet flow velocity of 14 m/s, (b) for  $5^\circ$  and 8 m/s.

The flat plate equipped with the DC plasma actuator was installed in the wind tunnel (see Fig. 3). Velocity field measurements were performed using the PIV system, with and without plasma. Results with streamlines deduced from velocity fields are shown in Fig. 10. The separation bubble size decreased with the electric discharge (angle of attack of  $2.5^\circ$ , inlet airflow velocity in the wind tunnel of 14 m/s, a Reynolds number of 187,000, Fig. 10.a), and the fully separated flow was re-attached beyond a bubble ( $5^\circ$ , 8 m/s,  $Re=107,000$ , Fig.

10.b). This clearly visible effect was obtained at rather high Reynolds numbers compared to those previously reported [6] (up to 68,600 in this mentioned work) also with a DC corona discharge on a flat plate.

#### **4. Conclusion**

A DC surface corona discharge established between two thin copper layer electrodes placed on each side of the plate attack edge is presented in this paper. Although the plasma appears as a homogeneous layer, measurements with a photomultiplier tube showed that it is, in fact, composed of a multitude of small, pulsed discharges, whose repetition frequency increases with applied high voltage.

The positive ion movement in the plasma induced airflow around the flat plate. Measurements with a pressure sensing probe indicate that the maximum mean velocity of ionic wind in the configuration studied was about 1 m/s. This value is quite low compared to the airflow in the wind tunnel, but even in these conditions, the presence of the plasma was efficient in reducing the separated flow on the flat plate in a subsonic wind tunnel, for a flow velocity of 14 m/s (Reynolds number of 187,000). This result encourages further studies on a wing airfoil in a subsonic wind tunnel.

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