Correlation between the EHD flow and the collection efficiency of an ESP

N. Zouzou, B. Dramane, E. Moreau, and G. Touchard

Abstract—**In this paper, particle velocity fields inside a wire-to-plane ElectroStatic Precipitator (ESP) are investigated experimentally using Particle Image Velocimetry (PIV). The main objective of this study is to analyze the effect of the ionic wind on the particle collection efficiency in such systems. The high voltage power supply waveform and the presence of a dielectric barrier are the major parameters taken into account.**

The submicron particles, with a mean size of about 0.3 µm, are generated from incense burning and introduced into the ESP in order to examine the collection efficiency of the ESP using an aerosol spectrometer.

PIV results show a strong interaction between the primary flow and the secondary flow (ionic wind). Near the wire electrode, the strong electric forces moved the particles from the central part of the channel to the plate electrodes. Within the drift region, the velocity magnitude depends essentially on the balance between the electric and the viscous forces.

As expected, the highest collection efficiency is obtained with the negative dc corona. At low frequency (< 30 Hz), the Dielectric Barrier Discharge (DBD) is as effective as the positive dc corona.

Correlation between the ElectroHydroDynamic (EHD) flow and the collection efficiency show that the optimum distribution of ionic wind in time and space is one solution for the improvement of electrostatic precipitation of submicron particles.

Index Terms— **Electrostatic precipitation, Collection efficiency, Particle image velocimetry.**

I. Introduction

ELECTROSTATIC Precipitators (ESPs) have been used for several decades to control air pollution in order to reach specific legislative emissions. Consequently, the collection efficiencies must approach and sometimes exceed 99.9% [1].

However, there is still a problem with the collection of submicron particles. In fact, several investigations have shown that the collection efficiency for submicron particles using an ESP is lower in the range from 0.2 to 2 µm [2-3]. For larger particles (> 2 µm), field charging is dominant. For smaller particles (< 0.2 µm), thermal diffusion prevails and diffusion charging becomes important [3].

The electrostatic precipitation depends essentially on the particle properties, electric field, space charge and gas flow field, among others. These parameters influence the balance between the electric and the viscous forces controlling the magnitude of particle drift velocity [4-5]. Furthermore, the collection efficiency is influenced by the interaction between the primary flow and the ElectroHydroDynamic (EHD) secondary flow induced by ionic wind [6-7]. This interaction generates more or less complex flow structures depending on the ESP construction [8-11].

In this paper, particle velocity fields inside wire-to-plane ESPs are investigated experimentally using Particle Image Velocimetry (PIV). The main objective of this study is to analyze the effect of the ionic wind on the particle collection efficiency. The high voltage power supply waveform and the presence of a dielectric barrier are the major parameters under consideration.

In the first part of the paper, the experimental setup is described. Then, results concerning the discharge characteristics are presented. The aim of the next part is to make correlation between the EHD secondary flow and the collection efficiency of the studied ESPs. Finally, conclusions and upcoming works are summarized.

II. Experimental Setup

A. Construction of the ESPs

The wire-to-plane ESP used in this investigation consists of two parallel electrodes (aluminum, 80-mm-length and 60-mm-width in x-direction and z-direction, respectively) as shown in Fig. 1. Both parallel electrodes are grounded. The high voltage electrode consists of a stainless steel wire (0.2-mm-diameter) aligned on the central axis of the channel. In the case of the ESP based on a dielectric barrier discharge (called DBD-ESP, Fig. 1a), the planar electrodes are wrapped on 2-mm-thick dielectric plates (Pyrex, 600-mm-length and 60-mm-width in x and z directions), which form the wind tunnel used for the PIV measurements. The distance between both dielectric plates is equal to 16 mm.

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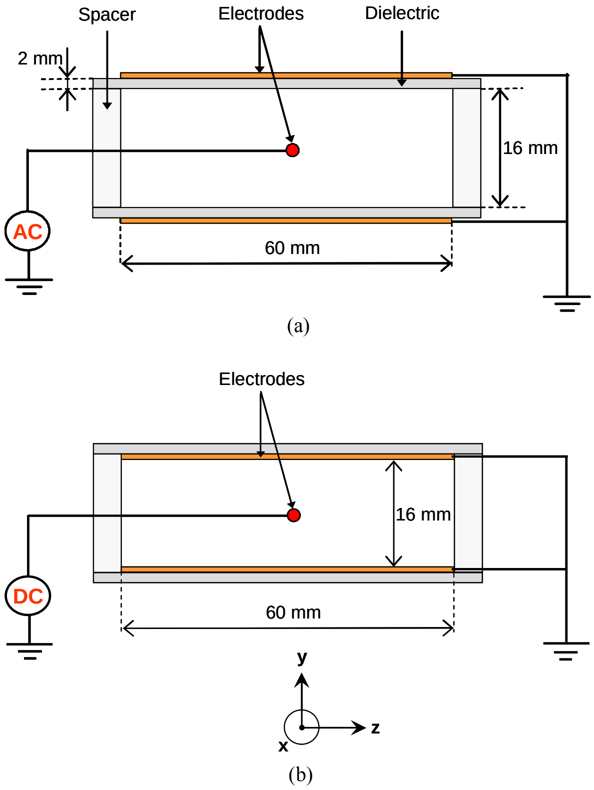

Fig. 1. Cross-section view of (a) DBD-ESP (b) DC-ESP.

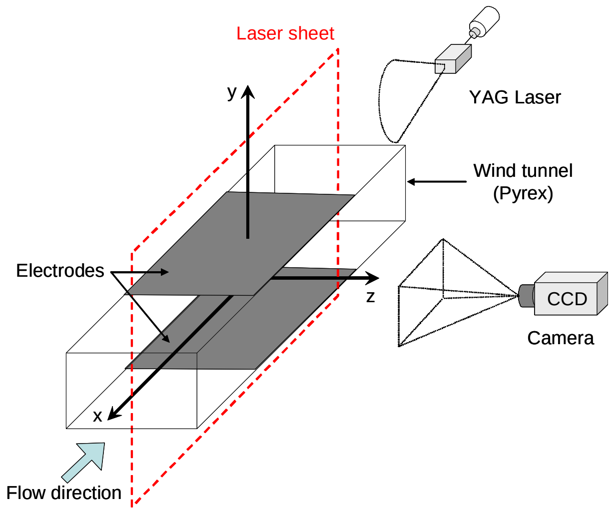

Fig. 2. Schematic illustration of the PIV measurements.

A similar geometry is used in the case of the ESP based on a dc corona discharge (referred as DC-ESP). Planar electrodes are flush mounted on the inner surface of the dielectric plates forming the wind tunnel, as shown in Fig. 1b.

B. Electrical Devices

Two types of high voltage waveforms are used: ac in the case of DBD-ESP and dc in the case of DC-ESP. The ac power supply system consists of a high voltage power amplifier (Trek, 30/20C, ±30 kV, ±20 mA), a function generator (Hameg, HM 8130), a current probe (shunt resistor of 100 Ω), a high voltage probe (internal probe of the amplifier) and a digital oscilloscope (Lecroy 424, 200 MHz, 2GS/s). An ac high voltage is applied to create the DBD inside the ESP. The voltage level varies from 6 to 20 kV and the frequency between 1 and 1000 Hz. More details on the electrical system can be found in [12-13].

The dc high voltage is applied using a dc power supply (Spellman SL 150, ±40 kV; ±3.75 mA, accuracy ≈ 0.1 kV). The power supply is protected by a ballast resistor of 10 kΩ. The current is measured with a digital multimeter (Meterman 37 XR, accuracy ≈ 1 µA).

C. Particle Tracking using PIV

Submicron particles, with a mean size of about 0.3 µm, are generated from incense burning and introduced into the precipitators in order to examine the EHD flow induced by different discharges. Inside the ESP, particle velocity fields are analyzed experimentally using PIV (Fig. 2). The acquisition system is a standard PIV system manufactured by LaVision. This system uses a mini YAG laser (30 mJ). Images are recorded by a CCD digital camera, with a resolution of 1376×1040 pixels. The frames are analyzed with Davis® software. We worked on a basis of 500 frames per series of measurements, which is sufficient to reach a statically converged time-averaged measure. The origin of the coordinate system is set at the centre between both parallel electrodes.

All the experiments are carried out at atmospheric pressure and room temperature.

D. Particle Counting

Inside the ESP, the particles are electrically charged and collected on the internal surface of the wind tunnel. In order to calculate the collection efficiency of the ESP, particle concentration in a diluted sample of the exhaust is measured using an aerosol spectrometer (Pallas, Model Wellas-1000, sensor range of 0.18-40 µm, concentration up to 10^5 particles/cm^3). More details about the particle counting system can be found in [12-13].

Since the conventional particle mass/volume collection efficiency cannot be applied to submicron particles due to the existence of heavier particles, collection efficiency in terms of number/volume is considered in this investigation.

The total number collection efficiency (η) is defined as follows:

$$\eta = 1 - \frac{N_{ON}}{N_{OFF}} \qquad (1)$$

where N_{ON} and N_{OFF} are the number of particles per cm^3 with and without discharge, respectively.

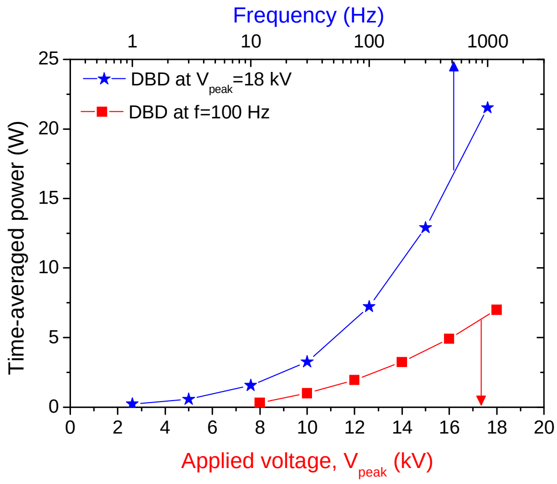

Fig. 3. Time-averaged power (P) versus applied voltage (V_{peak}) and frequency (f) in the case of DBD-ESP.

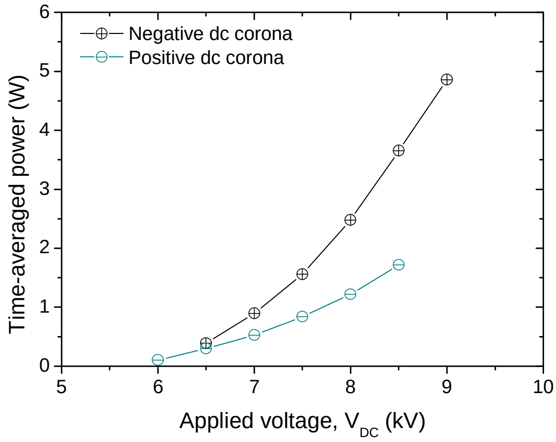

Fig. 4. Time-averaged power (P) versus applied voltage (V_{DC}) in the case of DC-ESP.

III. Results and Discussion

A. Electrical behaviour

Fig. 3 shows the evolution of the time-averaged electric power consumption as a function of the applied voltage and frequency in the case of the DBD-ESP. The applied peak voltage (V_{peak}) necessary to the ignition of the DBD depends essentially on the dielectric barrier thickness (2mm). By increasing frequency, high power can be injected in the system without arcing.

In the case of the DC-DBD (Fig. 4), the time-averaged power increases also with the applied voltage. At a given voltage, the electric power is higher with the negative polarity. This could be explained by the difference between the apparent mobility of negative charge carriers compared to positive ones. Because of corona-to-arc transition, the electric power is limited with the DC-ESP, especially in the case of the positive polarity.

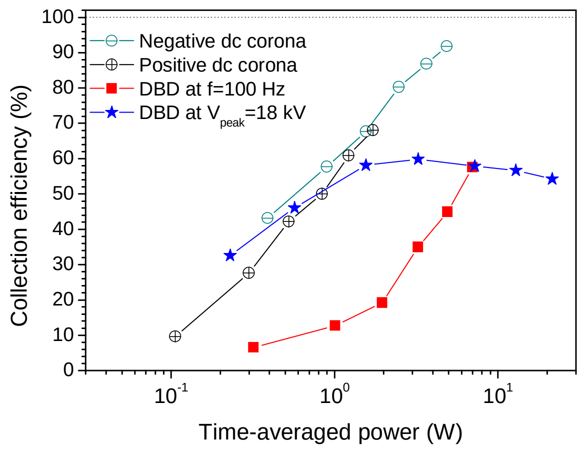

Fig. 5. Collection efficiency versus average power with DC-ESP and DBD ESP.

B. Collection Efficiency of the ESPs

Fig. 5 illustrates the evolution of the collection efficiency as a function of the electric power. The collection efficiency is greater at high electric powers in both ESP configurations. However, the collection efficiency reaches higher values (up to 92%) in the case of negative dc corona, where it is limited to 68 % in the case of the positive dc corona. Using DBD-ESP, the collection efficiency decreases at high frequency because of particle oscillations, and at low frequency due to the intermittent nature of the discharge [12]. Therefore, the collection efficiency of the DBD-ESP reaches at the same level as with the positive dc corona only at low frequency (<30 Hz).

Using the wire-to-plane ESP with or without dielectric barrier, the discharge is limited to the wire vicinity. Furthermore, the drift region is not large enough in the z-direction compared to the wind tunnel width (60 mm). Even if the interaction between the EHD secondary flow and the primary flow is strong, the particles entering in the channel near the vertical walls have a small chance to be sufficiently charged. Thus, the collection efficiency level can not reach 99%.

C. Particle Velocity Fields

The 2D particle flow fields measured in the measurement planes along the ESPs are shown in Fig. 6-8. They illustrate the velocity fields in the x-y plane at z=0 mm. The primary flow averaged velocity is U_o=1m/s (Reynolds number Re=1019).

Without discharge (Fig. 6a, 7a and 8a), the flow velocity fields confirms that the flow is laminar. After the establishment of the discharge (Fig. 6b, 7b and 8b), the particle flow velocity fields change significantly from that observed without discharge. Results obtained with either DC-ESP or DBD-ESP show a strong interaction between the primary flow and the secondary flow (ionic wind). Near the wire electrode, the strong electric forces moved the particles

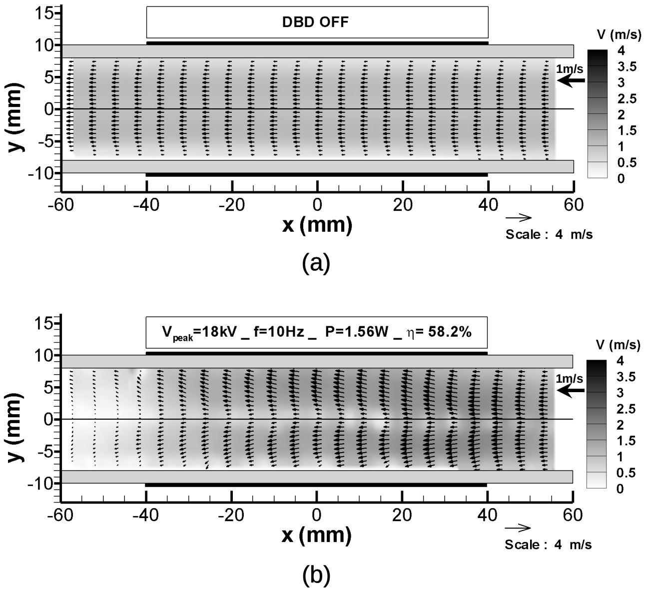

Fig. 6. Time-averaged velocity fields in the case of DBD-ESP: (a) without discharge, (b) with discharge.

from the central part of the channel to the plate electrodes. Within the drift region, the velocity magnitude depends on the balance between the electric and the viscous forces.

In a recent investigation, Niewulis *et al.* [14] suggests that in the ESPs with the longitudinal wire electrode, the particle flow in the ESP have a strong three-dimensional (3D) character. Consequently, analyzing the 2D particle flow patterns measured in one measurement plane is not sufficient for the understanding of the complex interaction between the primary flow and the EHD secondary flow. However, the wire electrode can be considered as the 'motor' of this interaction. This is way, a particular attention have been taken on the velocity fields in the vicinity of the wire in the x-y plane at z=0mm. Moreover, some particular cases are chosen in which time-averaged power and collection efficiency are almost similar (1.56W<P<1.72W and 58 %< η <68 %).

Whatever the ESP excitation, the discharge leads to the existence of a backward flow near the outlet, between x =-40 mm and x=-60 mm (the particles returns towards the discharge region). However, the flow structures in the drift region are affected by the ESP excitation. In the case of DBD-ESP (Fig. 6b), the time-averaged particle trajectories are bent toward the dielectrics with a strong increases in the time-averaged velocity magnitude. The influence of the frequency on the velocity magnitude will be discussed in the following section.

In the case of negative DC-ESP, the particles are accelerated and deflected toward the collecting electrodes in the first part of the discharge region (10 mm<x <40 mm). Downstream, the particles seem to follow the primary flow.

In the case of positive DC-ESP, the particles are first accelerated (20mm<x<40mm) before a deceleration (10mm<x<20 mm). The deceleration can be explained by an increase in the velocity z-component. For x<10 mm, the particle trajectories are turned toward the collecting plates.

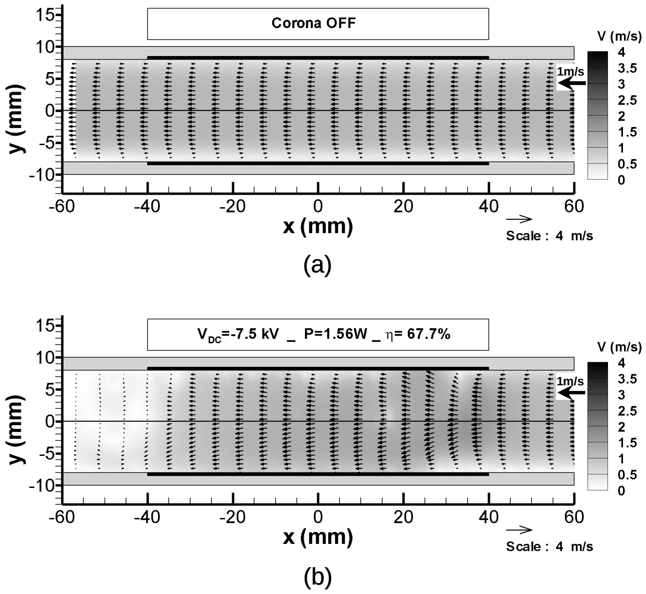

Fig. 7. Time-averaged velocity fields in the case of negative DC-ESP: (a) without discharge, (b) with discharge.

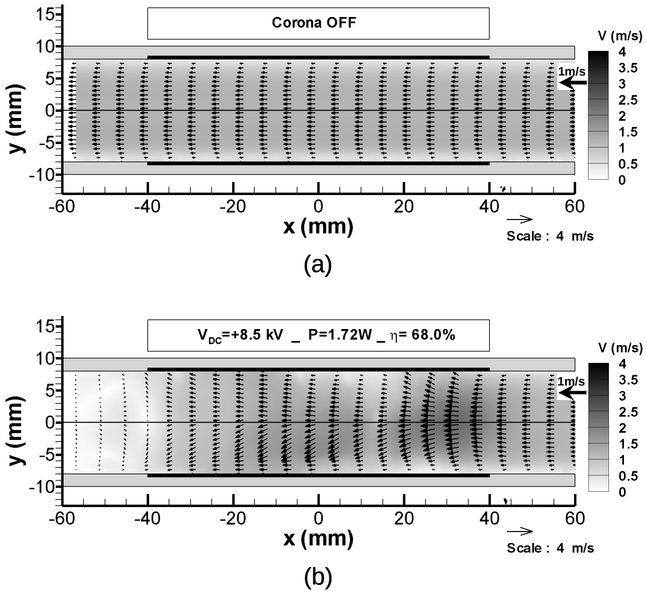

Fig. 8. Time-averaged velocity fields in the case of positive DC-ESP: (a) without discharge, (b) with discharge.

As it has been reported in the past [15-16], the negative dc corona generates discrete active spots called 'tufts' along the corona wire, while the positive dc corona gives a more uniform bright sheath around the wire. This is assumed to indicate a difference in the relative spatial distribution of positive or negative dc coronas. Therefore, the interaction between the primary flow and the ionic wind are completely different. In addition, the DBD-ESP did not present a resulted flow midway between positive and negative DC-ESP, because of the intermittent nature of the discharge and particle oscillations due to the bipolar charging during a complete period. Consequently, time-averaged velocity fields exclude the information concerning the particle deviations around the mean trajectories.

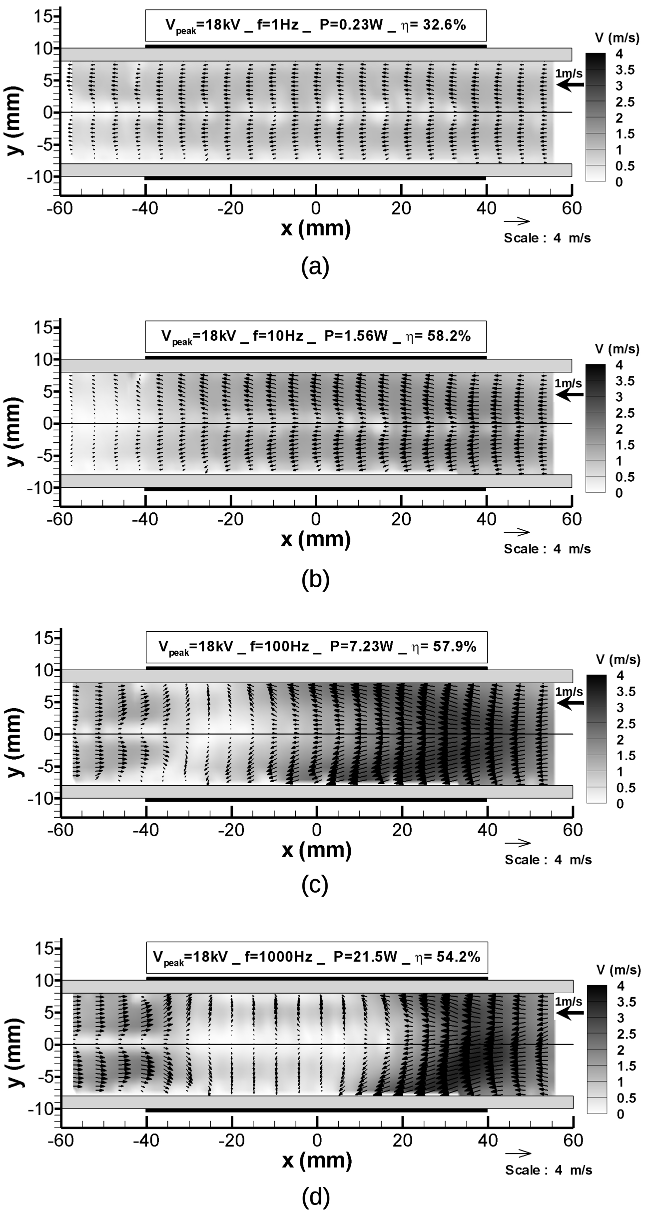

Fig. 9. Effect of frequency on the time-averaged vector fields in the case of DBD-ESP: (a) f=1 Hz, (b) f=10 Hz, (c) f=100 Hz, and (b) f=1000 Hz; Conditions: primary flow velocity Uo=1m/s and AC applied voltage=18kV$_{peak}$.

Even with the same electric power and collection efficiency, the EHD flow depends not only on the ESP construction but also on the discharge distribution in time and space.

D. Effect of frequency on EHD flow in DBD-ESP

Depending on frequency, the particle flow velocity fields in the DBD-ESP change significantly as illustrated in Fig. 9. With increasing frequency, the particles are more accelerated in the drift region with further pronounced backward effect.

In a recent publication dealing with the improvement of the DBD actuators for aerodynamic applications by Jolibois et Moreau [17], it has been shown that the ionic wind magnitude increases with the electric power whatever the applied voltage, the frequency and the high voltage waveform.

Fig. 5 shows that the best working point is obtained at low frequency in the case of DBD-ESP. Consequently, a strong time-averaged ionic wind developing in a large scale is not the only factor controlling the enhancement of electrostatic precipitation in such ESPs.

IV. Conclusion

The main objective of this paper was to analyze the effect of the ionic wind on the particle collection efficiency in the case of wire-to-plate electrostatic precipitator. The high voltage power supply waveform and the presence of a dielectric barrier were the major parameters taking into account. Two constructions have been studied: DC-ESP with positive or negative dc coronas and DBD-ESP with ac dielectric barrier discharge.

PIV results show a strong interaction between the primary flow and the secondary flow induced by the ionic wind in both ESP configurations.

As expected, the highest collection efficiency is obtained with the negative dc corona. In this case, the collection efficiency can reach 92% if the necessary power is provided. At lower frequency (<30 Hz), the dielectric barrier discharge is shown to be as effective as the positive dc corona.

Correlation between the electrohydrodynamic flow and the collection efficiency show that the optimum distribution of ionic wind in time and space is one solution for the improvement of electrostatic precipitation of submicron particles.

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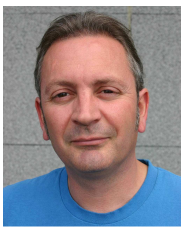

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His research interests focus on interactions between flows and electrical phenomena. Dr. Touchard is a member of the Russian Academy of Engineers. He established the French Society of Electrostatics in 1997 and has remained its Chairman.