

Dielectric barrier discharge type electrostatic precipitators - An overview

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Abstract

The collection efficiency of an electrostatic precipitator (ESP) depends essentially on the migration velocity of the particles toward the collection electrodes. This velocity is at its lowest level for particle sizes between 0.1 and 1 μm . Moreover, a recurring issue with DC discharges in air at atmospheric pressure is the build-up of significant space charges that may result in arc formation. To prevent such events, a straightforward approach consists in inserting a dielectric material between two electrodes. When subjected to an alternative electric excitation, this setup produces a discharge known as dielectric barrier discharge or DBD. This paper focuses on the study and development of a dielectric barrier discharge type electrostatic precipitators (DBD-ESP) for the capture of submicron particles. After the presentation of the basic configuration of DBD-ESP, a comparative analysis of the two primary types of DBD-ESP based on their discharge characteristics (filamentary or diffuse) is provided. Subsequently, a discussion on geometrical and electrical optimization is presented to enhance the collection efficiency. The second section of the paper explores the role of electrohydrodynamic flows (EHD) within the DBD-ESP, regarding the charging and collection mechanisms of submicron particles. Specifically, the distinct nature of EHD flows in a DBD-ESP is compared to the one observed in a conventional corona discharge ESP. Then, a theoretical model of particle movement in plane-to-plane DBD ESP allowing understanding the behavior of particles is presented, in order to show the interest of a DBD charger in the field of particle charge measurement. Finally, an exploratory study on the regeneration of subsequently polluted surfaces will be discussed at the end of this paper.

Keywords: Electrostatic precipitator, dielectric barrier discharge, collection efficiency, electrohydrodynamic flow.

1. Introduction

Health impact induced by airborne particles is no longer to be dismantled, particularly with regard to cardiovascular and respiratory effects [1]. Whether short-term or chronic exposure, fine and ultrafine particles are the most harmful to humans. For several decades, the scientific community has been interested in improving combustion and post-processing processes in order to reduce the mass of produced particles, which allows to meet increasingly stringent emission standards. The means of air filtration, which focus this interest, can be gathered into four categories of separation: mechanic, hydraulic, filter media or electric. Electrostatic precipitators (ESP) are distinguished from the first three processes by their ability to act on ultrafine particles with a diameter of less than 0.1 μm . For more than a century, research on ESP has made them more efficient, robust and energy efficient. However, many phenomena can still deteriorate their performance: dependence on resistivity and particle size, re-entrainment, back corona, extinction of discharge by space charge, among others. This led us to explore a new range of ESP based on the use of dielectric barrier discharges (DBD) to increase the potential of electrostatic precipitation of submicron particles. Then, particles' charging using DBD is discussed based on numerical studies. In the last section of the paper, results of surface regeneration by a nanosecond surface DBD are presented and discussed.

2. Electro-filtration of ultrafine particles using DBD type ESP

2.1 Basic configuration

At Pprime Institute (Poitiers, France), we explored for over 18 years the abilities of DBD in a single-stage ESP for the collection of submicron particles in the range from 0.1 to 1 μm . This researches naturally involves knowledge and control of the electric discharges at the origin of the space charge essential for the operation of an ESP. Different geometries have been studied and can be classified into two main families according to the shape of the discharge that characterizes them: filamentary or diffuse (Fig. 1).

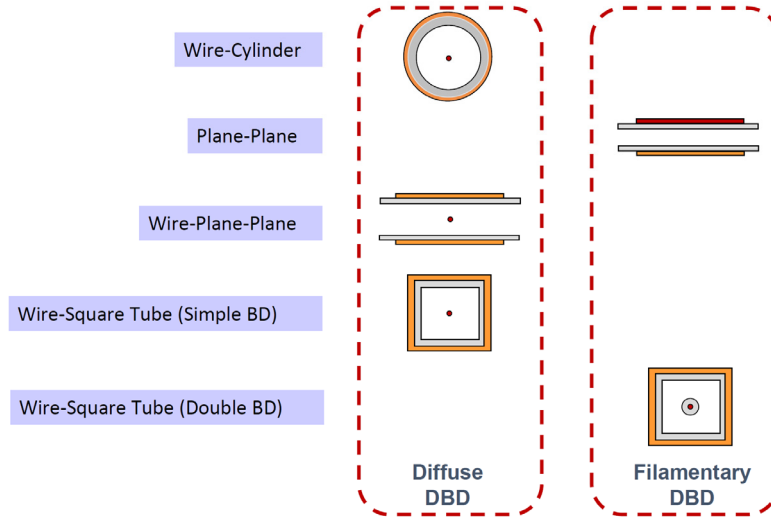


Fig. 1. Basic configurations used as DBD type ESP. Red color: active electrode or high voltage electrode; Orange: grounded electrodes; grey: dielectric barriers.

2.2 Principal characteristics

Fig. 2 shows a typical example of the evolution of voltage and discharge current as a function of time. During the positive alternation, the electric charges that accumulate on the dielectric barrier surface do not immediately relax. These charges induce an electric field that counteracts the external electric field in the gap, leading to the cessation of the discharge. In the subsequent alternation, the remaining charges enable new discharges to start at applied voltages lower than the initial discharge voltage.

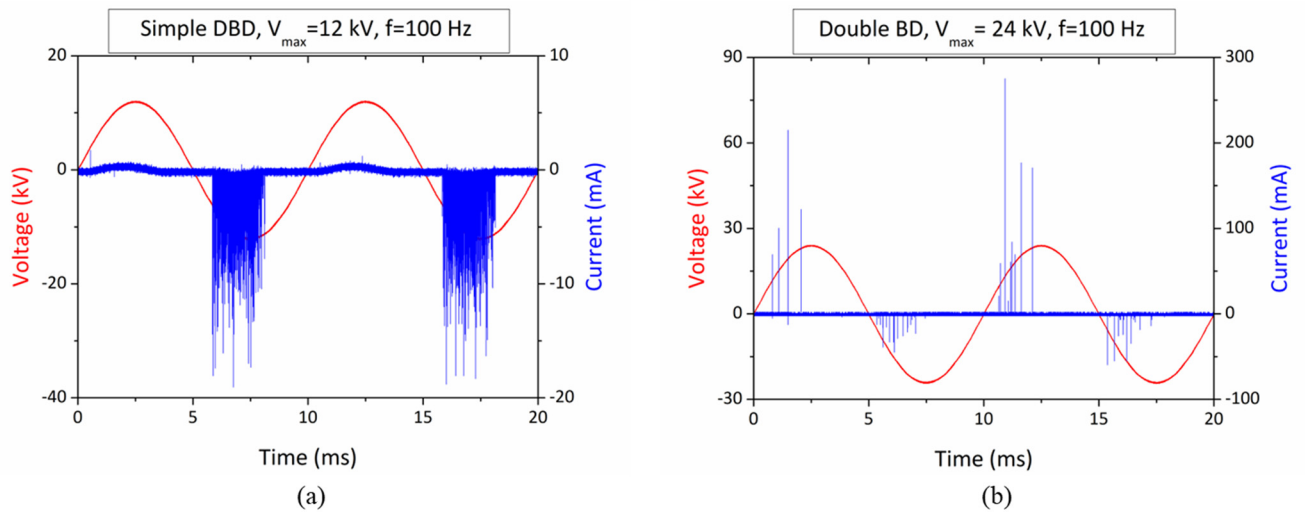


Fig. 2. Time evolution of the applied voltage and discharge current for (a) single barrier DBD-ESP and (b) double barrier DBD-ESP [2].

Within a wire-to-square tube (single barrier), the current waveform has a low amplitude and long duration peak (Fig. 2(a)) on the positive alternation while on the negative alternation, in addition to a similar peak, there are many very close pulses [2]. The current peaks represent the pseudo-DC current and the Trichel pulses. The establishment of pseudo-DC current corresponds to the corona-glow discharge regime. Overall, this ESP configuration promotes the establishment of a form of discharge that can be called «diffuse» throughout the active electrode (high voltage electrode).

For the wire-to-square tube (double barrier), the discharge obtained is «filamentary» with current pulses up to 300 mA as shown in Fig. 2(b). Current pulse level is limited by the high voltage amplifier. The discharge regime in this case is of the streamer's type.

It is important to note that having a dielectric material between the electrodes results in a higher discharge inception voltage and a shorter discharge gap length compared to conventional corona discharge-type ESP, which could be seen as a disadvantage.

2.3 Collection efficiency – diffuse versus filamentary

The collection efficiency of DBD type ESP is influenced by several parameters such as the amplitude of the applied voltage and its waveform, frequency, flow rate, geometric configuration, particle concentration, temperature, among others [3].

Fig. 3 shows the evolution of penetration compared to the average power consumption of a given frequency (100 Hz) in the case of single barrier DBD-ESP (diffuse) and double barrier DBD-ESP (filamentary) [2]. For a given level of penetration, the double barrier configuration requires less power than the simple barrier setup. This finding is crucial to cost reduction, as the active electrode (wire) in the double barrier configuration does not come into contact with the plasma, preventing degradation and contamination. However, for applications demanding high performances (up to 99.99%), the single barrier ESP remains the most suitable option.

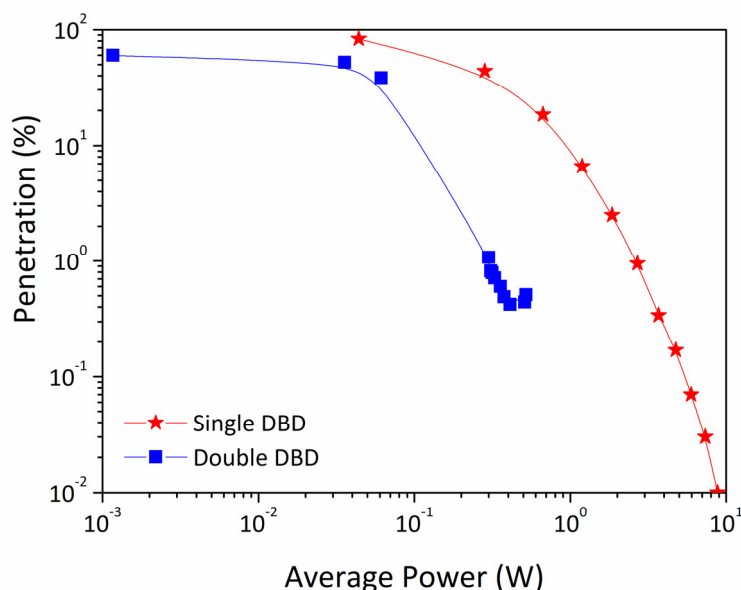


Fig. 3. Penetration *versus* average power of single DBD-ESP (diffuse discharges) and double DBD-ESP (filamentary discharges) [2].

2.4 Electrical and geometrical optimization

Starting from a square wire-square tube geometry, the influence of several geometrical parameters of an axisymmetric configuration on the collection efficiency has been studied. These include the diameter of the wire, the section of the tube, the number of collecting faces, the length of the counter-electrode and its discretization and finally, the influence of the presence of a second dielectric barrier on the active electrode. Table 1 summarizes the influence of the geometrical parameters studied so far on the performance of the DBD-type ESP of axisymmetric configuration.

Electrical optimization has shown that the use of a square voltage induces a clear improvement in the performance of the DBD type ESP. Therefore, the signal waveform has been optimized in order to improve the performance of the ESP (Fig. 4). In our experimental conditions and in the available ranges of the studied parameters, it appears that the reduction of the discharge time, the presence of an offset, the reduction of rise and fall times does not improve the performance of the ESP [5]. This is mainly due to the decrease of the ion density in the inter-electrode space due to the reduction of the duration of the discharge activity.

Table 1. Classification of the studied geometrical parameters according to their effect on the performance in the case of axisymmetric DBD-ESP [4].

Weak effect	Significant effect
• Tube shape • Active wire diameter • Number of faces	• Tube section • Length of grounded electrode • Discretization of the grounded electrode • Double dielectric barrier

However, a rising voltage plate positively impacts the performance of the DBD-ESP (Fig. 4) [5]. Indeed, the gradual increase of the voltage level during an alternation allows an increase of the applied electric field, which compensates the inverse electric field generated by the electric charges deposited on the dielectric barrier. Therefore, the electric field in the inter-electrode space remains strong enough to stimulate the electric discharge activity.

This result opens new perspectives on the use of DBD type ESP powered by a current switch, allowing to have a linear dynamic of the curve of transferred charges on each half-alternation. In fact, the charge and drift processes of particles are favored when the discharge activity is as long and as intense as possible over a period of time.

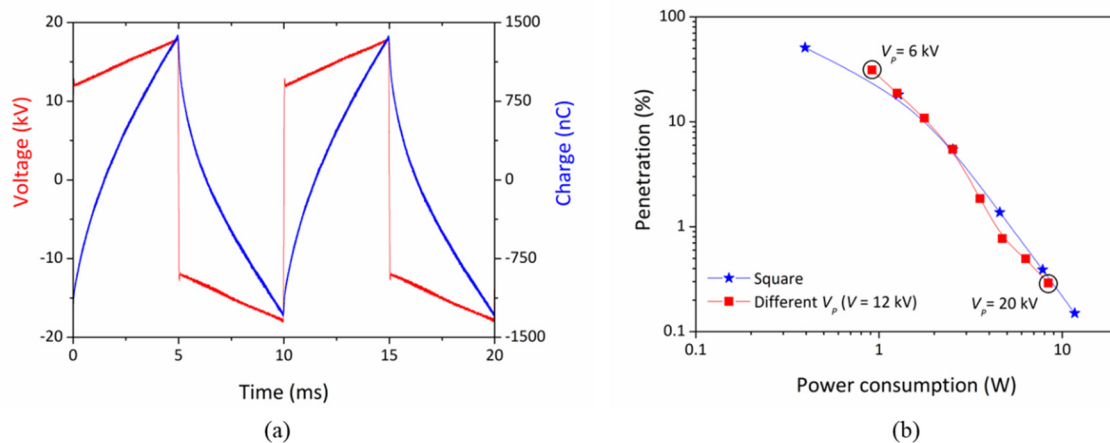


Fig. 4. (a) Time evolution of the transferred electric charge for rising voltage waveform. (b) Penetration *versus* average power for different voltage plateau [5].

3. Electro-hydro-dynamic phenomena

Inside an electrostatic precipitator, the flow of particles has two components: the main flow that can be measured without an electric field and the secondary flow, or electrohydrodynamic flow (EHD), which is produced by the electric discharge. The EHD flow results from the transfer of the kinetic energy of ions (electric wind or ionic wind) and charged particles to the neutral molecules of the gas [6]. Indeed, several experimental and numerical studies showed that the increase in the concentration of submicron particles in the inter-electrode space results in the decrease of the discharge current and the increase of the turbulence [7, 8]. Thus, the particle movements within an ESP depend mainly on the electric field, the space charge, the gas flow velocity, the physical parameters of the particles, the geometry of the electrodes and the EHD flows, factors that interact with each other. However, the effect of EHD phenomena on the performance of an electrostatic precipitator still causes divergence within the scientific community. Some researchers believe

that particle collection efficiency deteriorates with the intensification of secondary flows [9, 10], while others claim that this effect is negligible [11, 12].

Prime Institute is one of the few research laboratories allowing the realization of advanced experimental studies of electrohydrodynamic phenomena within electrostatic precipitators in general, and those with dielectric barrier discharges in particular. In this section, we will discuss the role of EHD flows in the charge and collection mechanisms of submicron particles in the presence of a dielectric barrier discharge. Then, we focus on the interaction between streamers and particles in the case of filamentary DBD type ESP.

3.1 Effect of the electric wind on the collection efficiency

Compared to DC type ESP, DBD type ESP offers two additional control parameters: the frequency and the waveform of the voltage applied. Fig. 5 shows the mean velocity fields for four frequencies: 1, 10, 100 and 1000 Hz in the case of wire-to-plane geometry [13]. For an increasing frequency, the velocity of the particles is more important in the drift zone, with as a consequence an intensification of a flux-return phenomenon (return of the particles downstream towards the discharge zone). Indeed, the particles are first accelerated at the entrance of the active zone before initiating a movement out of the measurement plane. It is therefore the absence of particle movement in the measurement plane that explains the zero-velocity recorded in the middle of the high-frequency active zone. The phenomenon operating in this area closely resembles to that observed in DC type ESP by Niewulis *et al.* [14]. Indeed, in this region, convective cells are formed in the right angles of the channel, driving all the matter (particles) in the middle of the channel and creating a zone of depression. This vacuum zone behaves like a «pump» that sucks the flow from the outlet of the channel to compensate for the absence of matter in the middle. The result at the outlet is an acceleration of the particles in the opposite direction to that of the main flow.

Furthermore, the electrical power increases with frequency, which results in an intensification of the electric wind, while the collection efficiency increases, goes through a maximum before slightly decreasing (Fig. 5). Thus, the particle trajectories indicate the topology of the electric wind generated by the discharge. Based on these observations, it is concluded that the mean electric wind is not *a priori* an important parameter for particle collection in such a geometry.

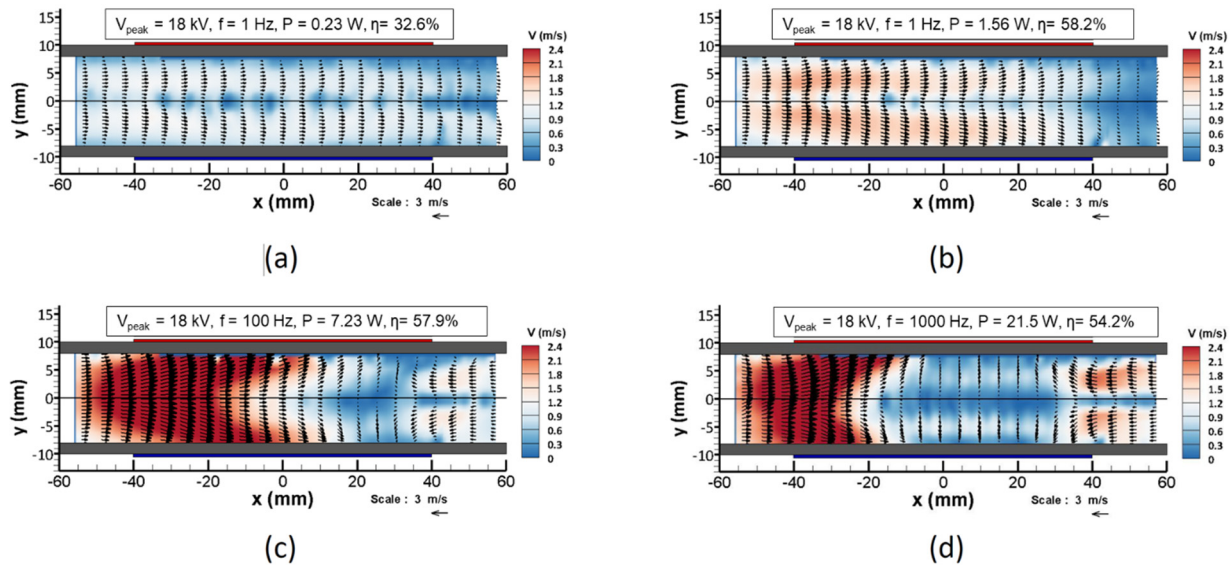


Fig. 5. Effect of frequency on time-averaged vector fields in the case of wire-to-plane DBD-ESP [13]. Geometry: 2 mm thick dielectric plates (Pyrex); 60 mm width in z directions; and 16 mm gap.

3.2 EHD phenomena induced by filamentary discharges

In a conventional ESP, the particles are charged in the inter-electrode space by the ions produced near the active electrodes. The electrically charged particles are then driven by the Coulomb force due to the electric field present in the inter-electrode space. Their migration to the collection electrodes is also affected by the

electric wind and the viscous force associated with the fluid flow [13]. In general, particles have three-dimensional (3D) trajectories.

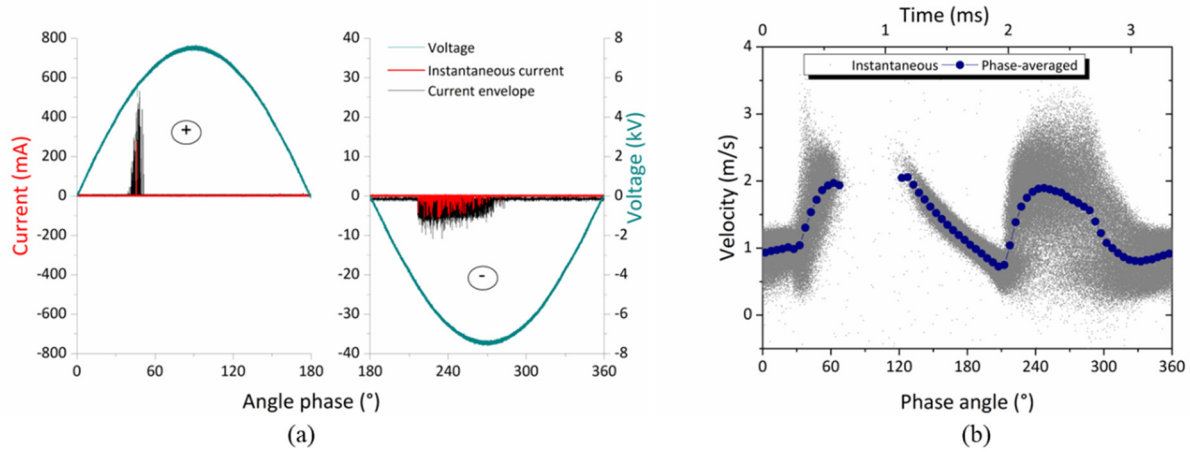


Fig. 6. (a) Typical waveforms of applied voltage and current for wire-to-plane configuration. (b) Phase reconstruction of time-resolved velocity obtained by using LDV technique [19].

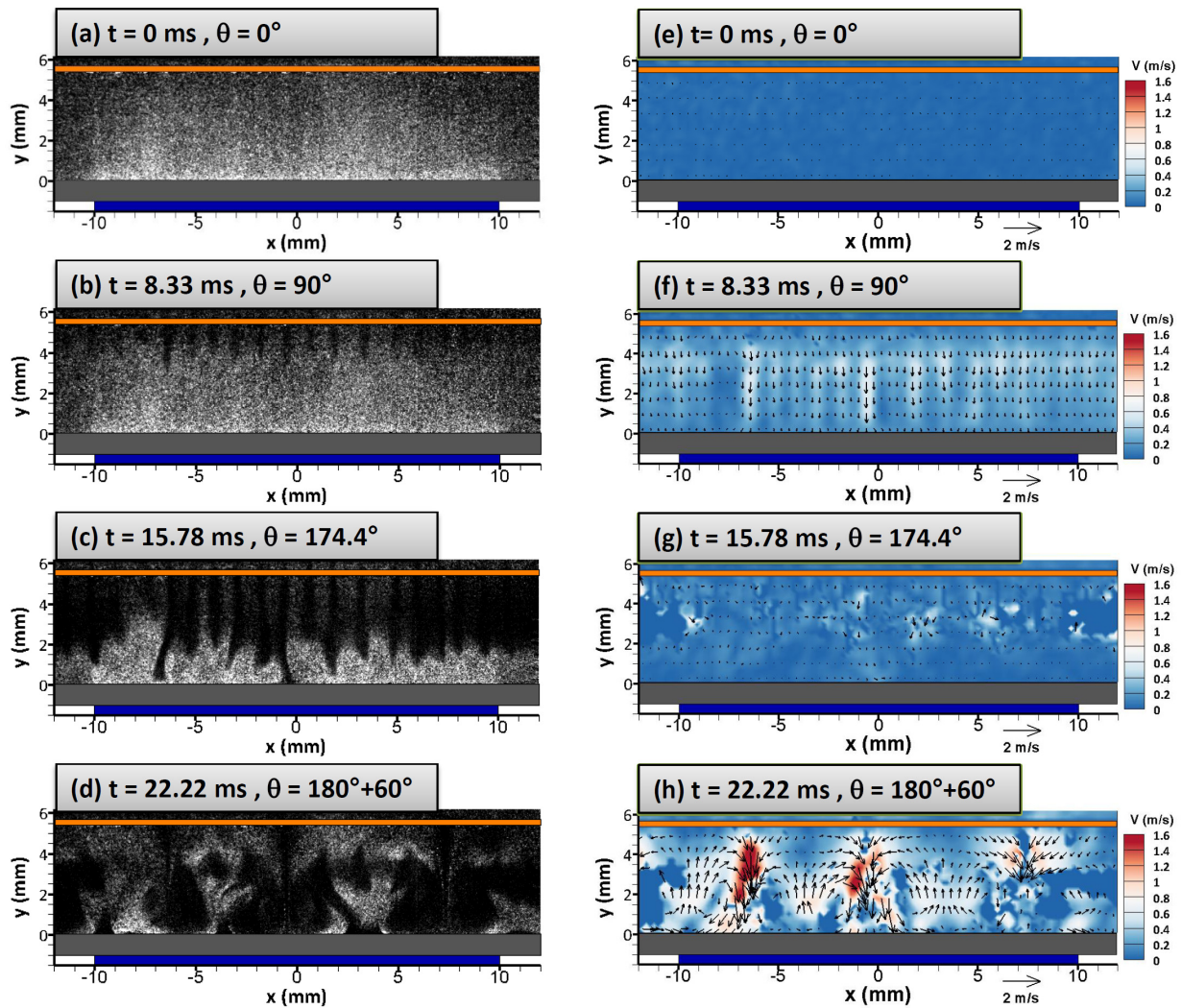


Fig. 7. Grey-level images and velocity vector fields measured using time-resolved PIV in the case of wire-to-plane configuration [19].

In the case of DBD type ESP operating in diffuse regime (such as in wire-tube configurations), the charge of the particles is bipolar [15]. With each alternation of the voltage signal, the particles receive charges of the same sign as the polarity of the active electrode (wire for instance), which alternates between positive and negative. When the voltage is in its positive half-cycle, the polarity of the wire is positive, as are the charges received by the particles. The electric field then decreases from the wire to the tube, resulting in particle movement in the same direction. When the voltage switches to the next half-cycle, the polarity of the wire becomes negative, and the electric field decreases from the tube to the wire. However, the particles initially charged positively first go through a neutralization phase before becoming negatively charged. During this process, these positively charged particles are subjected to the electric field and move in the same direction as it, from the tube to the wire [15].

The charge and drift process of the particles are completely different in the case of DBD type ESP operating in filamentary regime with a streamer type breakdown. Several phenomena can be observed in relation to the propagation of filaments through the inter-electrode gap in the presence of submicron particles. During the propagation of a filament, the particles suddenly disappear at its location as shown in Fig. 6 (results obtained by using Laser Doppler Velocimetry or LDV) and Fig. 7 (results obtained by using Time Resolved Particle Image Velocimetry or TR-PIV). This could be explained by a fast diffusion charge mechanism based on the contribution of electrons. Thus, charged particles can be collected during the initial stage of the process leading to the formation of plasma and involving electrons and positive ions.

After the filament propagates through the inter-electrode space, the particles usually drift in the direction of the electric field (Fig. 7 (f)), which means that the net charge of the particles is positive. This result is mainly due to the positive ions that remain in the inter-electrode space due to their significantly lower electric mobility than electrons [16–18].

4. Particle charging using DBD

4.1 Numerical study of particle charging

A new theoretical model of particles' movement in a filamentary DBD type ESP has been developed within the ElectroFluidDynamic group at Pprime Institute in 2016 [20]. The model is based on field-diffusion particle charging theory, classical movement equations and simplifying assumptions. In order to evaluate the charge, the velocity, the trajectory, and the collection efficiency of particles, two kinds of forces are considered. The first one is the electric force applied by the electric field on charged particles, and the second one is the drag force, which represents the resistance of the air to particle movement.

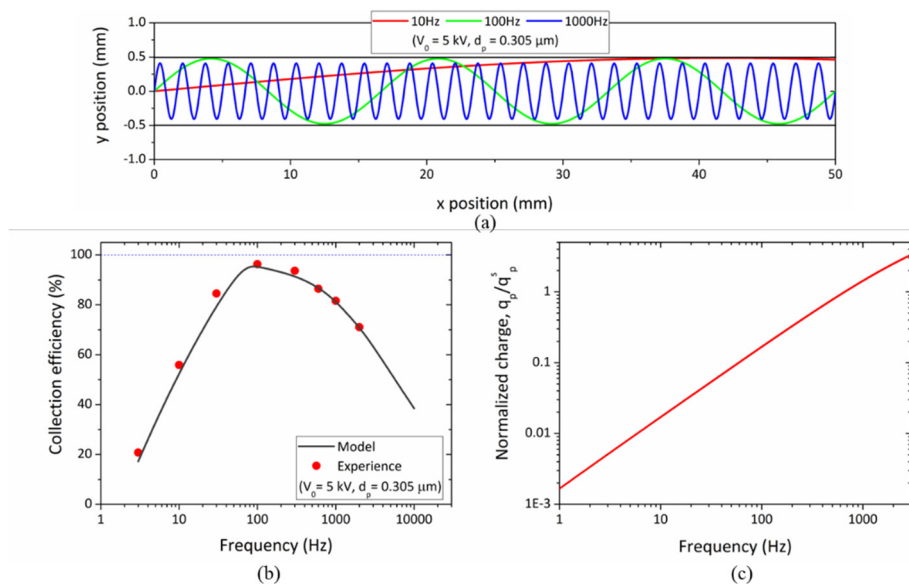


Fig. 8. Submicron particles' trajectory and collection efficiency in a miniature planar DBD-ESP. (a) Effect of the frequency on the particle motion. (b) Theoretical collection efficiency *versus* frequency. (c) Evolution of the normalized particle charge as a function of frequency [20].

Fig. 8 shows the effect of frequency on particle trajectories, the collection efficiency and particle charge level. The particles have an oscillatory motion caused by the alternating electric field (Fig. 8 (a)). The amplitude of oscillations (y_{max}) decreases with the frequency as demonstrated in [20]; this is why the collection efficiency falls down at high frequencies although the particle charge is higher (Fig. 8 (b)). This finding is particularly interesting for applications that require higher particle charging with lower particle collection, such as particle chargers. For these applications, DBD operating at high frequencies could be a solution, as indicated in Fig. 8 (c). At low frequencies, the amplitude of oscillations is high but there is not enough time for the particles to oscillate, that causes a diminution of particle collection efficiency [20].

4.2 DBD chargers

The instruments used for ultrafine particle metrology can detect a wide size range of particles, from a few nanometers to tens of micrometers, utilizing different physical principles. The most commonly used methods are based on optical and electrical principles. Electrical measurement techniques, such as the Electrical Low Pressure Impactor (ELPI+) and the Scanning Mobility Particle Sizer Spectrometer (SMPS), evaluate the accumulated charge on particles. Optical methods, like the Condensation Particle Counters (CPC) and aerosol spectrometers, are used to detect aerosols with diameters greater than $0.18 \mu\text{m}$. In this field, we introduce a new sensor designed for rapid monitoring and determination of the filtration efficiency of an electrostatic precipitator. This sensor measures the electric charge of particles at the output of a dielectric barrier discharge device, which is used as a particle charger [21].

Fig. 9 (a) shows a typical example of the evolution of the electric charge Q over time in a plane-to-plane DBD geometry [21]. The charge difference ΔQ represents the total electric charge of the particles as they exit the capacitive sensor during the transition from DBD_{ON} to DBD_{OFF}. To validate the results obtained with the capacitive sensor system, a comparative study was conducted using an ELPI+ positioned downstream of the sensor. The ELPI+ employs a positive corona discharge to charge the particles until they reach saturation, then classifies them by size across 14 sensing stages connected to electric sensors that quantify the total particle charge. The comparison results presented in Fig. 9 (b) show a similar tendency and charge density level for both detection systems. This outcome is significant as it demonstrates the robustness of the capacitive sensor against variations in total particle charge due to discharge behavior changes in the charger.

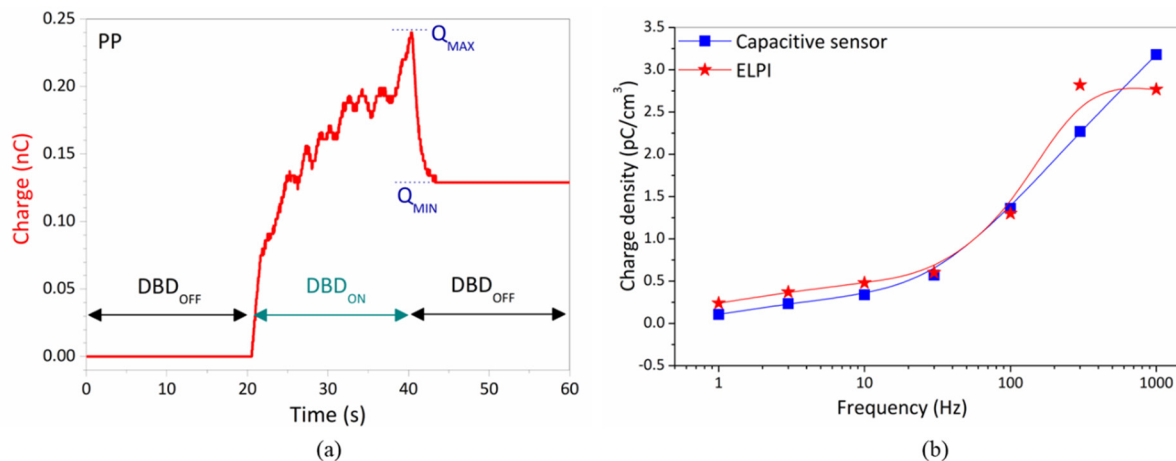


Fig. 9. (a) Time evolution of the charge within the sensor. (b) Variation of the charge density as a function of the frequency in the case plane-plane DBD charger [21].

5. Surface regeneration using surface dielectric barrier discharges

Ultrafine particles generated by diesel combustion can be collected using an electrostatic precipitator. Like any filter, it must be cleaned and maintained periodically to preserve its performance. Therefore, after the collection of ultrafine diesel particles, they must be incinerated or swept from the surface in order to be easily collected and processed by another process. With this in mind, we explored at Pprime Institute the possibility of regeneration (in the sense of cleaning) of soot-polluted surfaces using surface DBD. Indeed, this discharge

could respond to this problem through the action of: 1) electric wind generated near the wall, where the particles are deposited, to sweep them away from the contaminated surface; 2) The Coulomb force exerted on electrically charged particles embedded in the applied electric field; 3) The ozone molecules and oxygen radicals it generates, allowing soot oxidation even at low temperatures ($< 100\text{ }^{\circ}\text{C}$ [22]). Regarding the latter mechanism, Masuda and Moon [23] observed in 1983 the ability of corona discharges to oxidize soot to produce carbon monoxide and carbon dioxide (CO and CO_2). They showed that the rate of this oxidation is improved with the increase of the discharge activity, the concentration of oxygen and the temperature of the gas. Other investigations have confirmed this effect with volume dielectric barrier discharges [22–26].

In this section, the results of surface regeneration by a nanosecond surface DBD are presented. Fig. 10(a) shows typical waveforms of the current with and without the presence of particles in the case of negative high voltage pulses [27]. The waveforms are acquired 30 s after the application of the voltage. The signature of two well resolved peaks is observed during each transition of the applied voltage (from 0 to -10 kV then from -10 to 0 kV). The first current peak, related to the capacitive effect, is not sensitive to the presence of particles on the dielectric surface. The second peak is due to the occurrence of the discharge. Its magnitude becomes higher with the presence of particles, due to the enhancement of the surface electrical conductivity.

The evolution of electric power consumption with the treatment duration is shown in Fig. 10 (b) [27]. As expected, the power is higher with the presence of particles. This is explained by the fact that the soot layer makes the surface of the dielectric more conductive. Thus, the electric field near the HV electrode edge still at higher level because the deposited charges migrate far from the active area. After 10 min of treatment, the electric power becomes close to that measured in the case of a clean surface. Therefore, the power measurement could be considered as a good indicator of surface treatment progress.

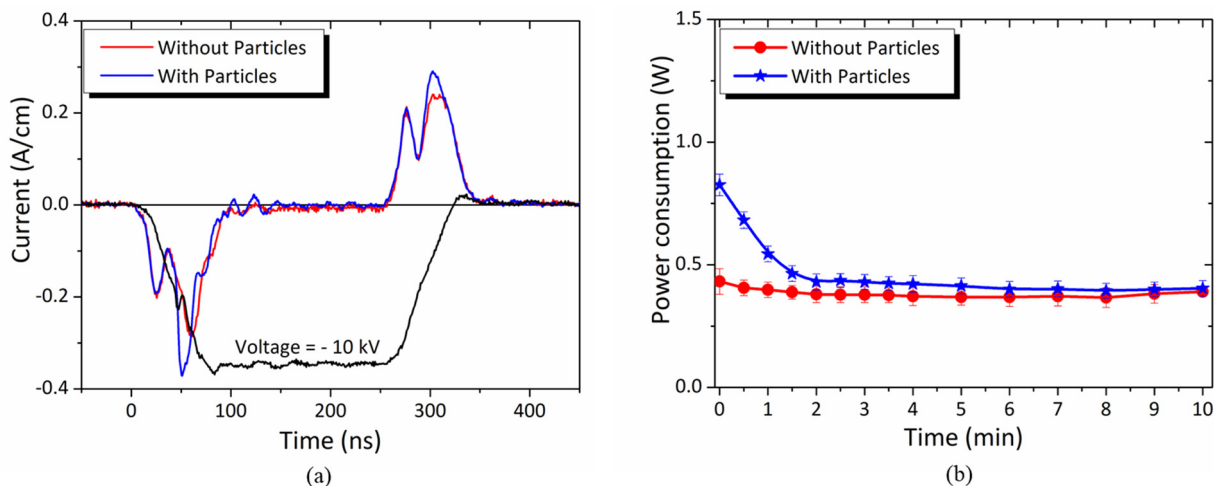


Fig. 10. (a) Time evolution of the current per unit length of the electrodes after 30 s of treatment.
(b) Influence of the presence of particles on power consumption [27].

Fig. 11 shows the typical top view photographs of the reactor after only 2 min of treatment for both positive and negative nanosecond pulsed voltages. The photographs show the high voltage electrode, in the first plane, placed on a transparent glass dielectric barrier (2 mm thickness). The grounded electrode is positioned under the dielectric barrier. Both electrodes are placed edge to edge. Then, soot particles were deposited on the glass and part of the high voltage electrode.

In the case of positive pulses, the treated area extends up to 13 mm from the active electrode. The regenerated zone is more or less uniform along the HV electrode. In the case of negative pulses, the treated area is completely different compared to the positive case. It has the shape of plume channels connected to the HV electrode. Consequently, the footprint of the discharge on the soot deposit is very similar to the shape of the plasma layer on a clean surface. Other measurements, has shown that the soot particles are reduced in size during the regeneration due to their interaction with the SDBD [27].

Other investigations on the same subject have been conducted by other researchers recently, using intermittent DBD [28] or floating electrodes DBD [29].

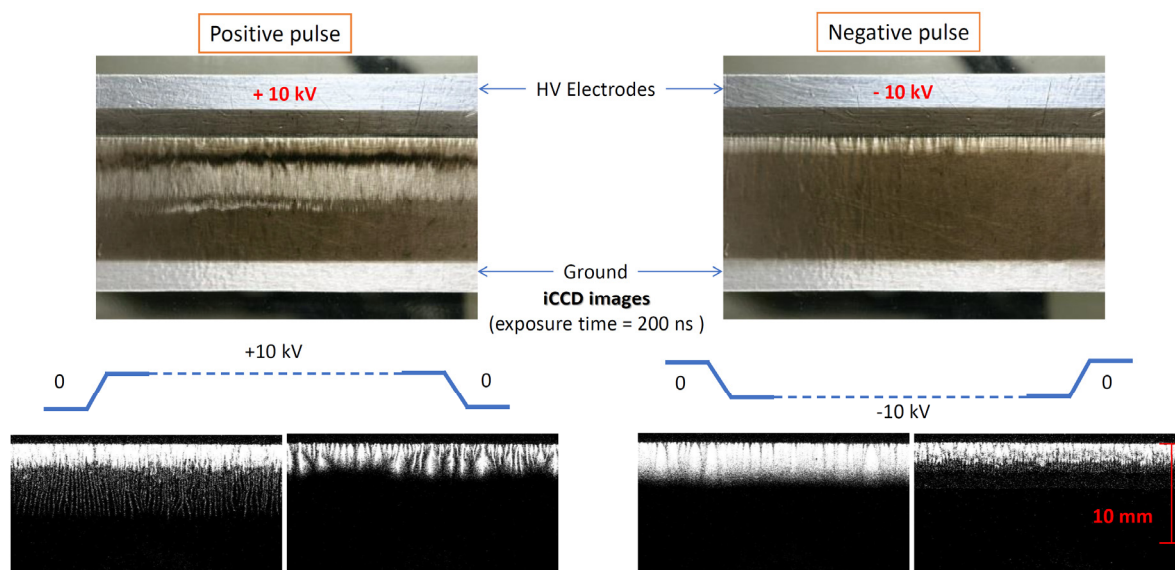


Fig. 11. Typical reactor photographs during surface regeneration [27].

6. Conclusion

In this paper, we showed that it was possible to capture submicron particles by electrostatic precipitation using a dielectric barrier discharge. We have been studying this new electrofiltration method continuously since 2006 within Electrofluidodynamic group at Pprime Institute (Poitiers, France). The main results obtained can be summarized as follows:

- DBD type ESPs can be classified into two main families according to the form of the discharge that characterizes them: filamentary or diffuse. For example, axisymmetric geometries under sinusoidal excitation are generally favorable to the formation of a corona-glow diffuse discharge. The latter can easily transit to a filamentary discharge of streamer type by modifying the geometric configuration (addition of a second dielectric barrier) or the electrical excitation (excitation by a positive nanosecond impulse voltage). In comparable situations, filamentary discharge paradoxically offers better efficiency in collecting sub-micrometer particles at the same energy cost as a diffuse discharge.
- The structure of the EHD flows depends not only on the geometry of the ESP, but also on the temporal distribution of the discharge (case of DBD type ESP) and its spatial distribution (case of corona DC type ESP). Also, A strong electric wind that develops on a large scale is not the main factor controlling the improvement (or degradation) of electrostatic precipitation in a DBD type ESP.
- Time-resolved techniques (PIV and LDV) revealed two mechanisms at the origin of submicron particle collection with a filamentary discharge regime. After the propagation of filaments, the residual positive space charge plays an essential role in the charge mechanism of the particles allowing their drift in the same direction as the electric field. During the propagation of a filament, the particles suddenly disappear at the same location of the filament, due to a mechanism that is still not fully understood.
- The theoretical model of particle motion in plane-to-plane DBD ESP allowed us to understand the behavior of the particles as well as the effect of the different experimental conditions on their charge and their trajectory and the effect of the latter on the collection efficiency. For instance, numerical results showed that the particle charge may exceed the saturation limit charge at high frequencies indicating that the diffusion charging process is very important. Thus, DBD charger coupled with a capacitive sensor can be used to measure particle's charge.
- The exploratory study on surface regeneration polluted by soot shows very interesting results and opens promising prospects for regenerating pipe walls in a large number of combustion processes.

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