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# Frequency effect on particles collection efficiency in planar DBD-ESP

A.Zouaghi<sup>1,2,\*</sup>, N. Zouzou<sup>2</sup>, A. Mekhaldi<sup>1</sup>, R. Gouri<sup>1,3</sup>

<sup>1</sup>Laboratoire de Recherche en Electrotechnique, Ecole Nationale Polytechnique d'Alger, 16200, Algiers, Algeria

<sup>2</sup>Institut Pprime, CNRS, Université de Poitiers, ISAE-ENSMA, F-86962 Futuroscope Chasseneuil, France

<sup>3</sup>Ecole Nationale Supérieure de Technologie, 16012, Algiers, Algeria

\*Corresponding author: [ayyoub.zouaghi@g.enp.edu.dz](mailto:ayyoub.zouaghi@g.enp.edu.dz)

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## Abstract

In this paper, the effect of frequency on the performance of a plane-to-plane dielectric barrier discharge electrostatic precipitator (DBD-ESP) is investigated experimentally. The typical characteristic quantities of the filamentary discharge such as the current waveform and the corresponding Q-V curve are presented and discussed. Then, a parametric study is carried out to evaluate the effects of the applied voltage amplitude and frequency on the collection efficiency of submicron particles within the size range from 0.2 to 0.7  $\mu\text{m}$ . The main results indicate that the particles penetration increases at low frequencies because of the low charge of particles and at high frequencies because of fast particles oscillation.

## 1. Introduction

The human industrial activities are responsible for a great part of the pollutant emissions in the atmosphere at both local and global levels. One of the major actors of air pollution is the suspended particles. They have a harmful effect on both nature and human health. The smaller ones could penetrate into the respiratory system causing numerous health problems such as asthma and lung cancer. Consequently, environmental standards become increasingly severe [1-3].

The electrostatic precipitator (ESP) is one of the most common devices to remove airborne particles from air in both industrial and living environments. This efficient operation depends essentially on the particles properties, the applied electric field, the space charge, and other forces related to the fluid flow and ionic wind. The conventional electrostatic precipitators use the corona discharge to produce ions in order to charge and collect them through electric forces [4-8]. Despite, the use of DC corona discharge presents some risks for HV power supplies due to arc transition. Recently, many studies are focusing on developing lab-scale dielectric barrier discharge type electrostatic precipitators (DBD-ESP). In fact the

DBD prevents arc transition due to the presence of at least one dielectric barrier between the electrodes.

In previous research works, the DBD has been used successfully for particles collection in planar, wire-to-cylinder and wire-to-square tube configurations [9-11]. It has been also used as a precharger in two-stage type electrostatic precipitators, where charging and drift processes are performed separately [12, 13]. Furthermore, the DBD type ESP has been shown to be efficient for simultaneous removal of particle and nitrogen oxides ( $\text{NO}_x$ ) from air [14, 15].

In the present work, the authors focus on the effect of frequency on the performance of plane-to-plane DBD electrostatic precipitator. The submicron particles under investigation are ranging from 0.18 to 0.7  $\mu\text{m}$ . The filamentary DBD discharge is obtained by applying an alternative high voltage through 1 mm air gap and double 180  $\mu\text{m}$  dielectric layers. In the first part of the paper, the experimental setup is described. Then, the electrical behavior of the filamentary discharge is investigated by analyzing the discharge current waveform, Q-V curves and the average power consumption. After the electrical study, the performance of the DBD-ESP is investigated using an aerosol spectrometer. A parametric study is carried out to evaluate the effects of the applied voltage, particles size and flow rate on the efficiency for both low and high frequencies. 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 performance of the DBD-ESP is described using particles penetration.

## 2. Experimental setup

The experimental setup, illustrated schematically in Fig. 1, consists of 3 parts: the DBD-ESP, power supply and measurement section and particles generation and counting sections.

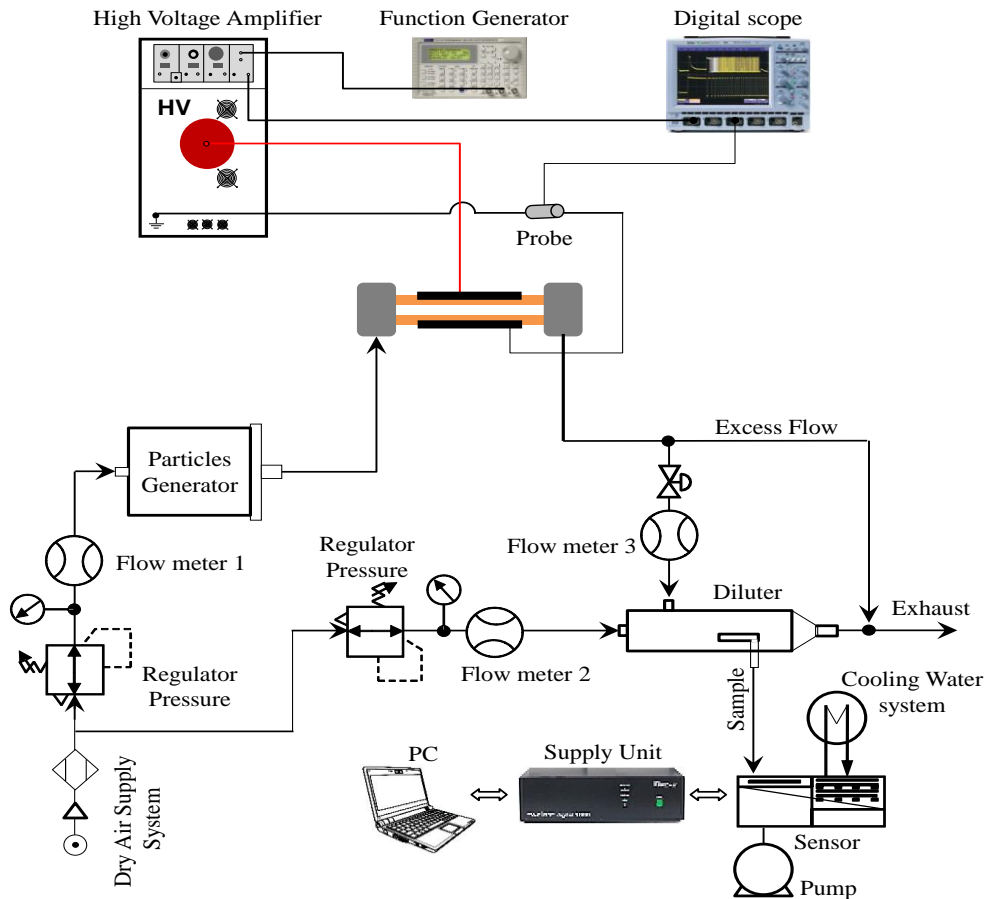


Figure 1. Schematic illustration of the experimental setup.

### 2.1. Design of the planar DBD-ESP

The plane-to-plane dielectric barrier discharge ESP studied in this work is represented in Fig. 2. It consists of two parallel plate electrodes; one of them is grounded and the other one is connected to ac high voltage power supply. Each electrode is made of 80  $\mu\text{m}$  thick copper foil (50 mm in length and 10 mm in width) covered by a dielectric layer made of polyimide (Adicaz, AHT006L300-L) with a thickness of about 180  $\mu\text{m}$  (this thickness is obtained by stacking three elementary layers of about 60  $\mu\text{m}$ ). The discharge gap is adjusted to 1 mm, which delimitates the active volume to about 500  $\text{mm}^3$ .

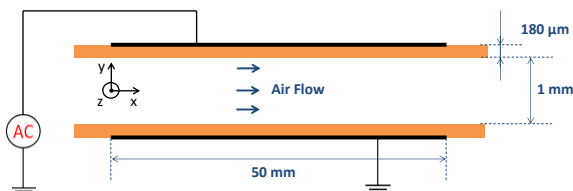


Figure 2. Cross-sectional view of the studied DBD-ESP.

### 2.2. Power supply and measurement

The ac power supply system consists of a high voltage power amplifier (Trek, 20/20C,  $\pm 20$  kV,  $\pm 20$  mA), a function generator (Hameg, HM 8130), a current probe (shunt resistor of 100  $\Omega$ ), a high voltage

probe (internal probe of the amplifier), and a digital oscilloscope (Lecroy 424, 200 MHz, 2GS/s). The transferred charge is measured with a capacitor of 33 nF connected in series with the ESP. The voltage level varies from 4 to 10 kV, and the frequency varies between 1 and 2000 Hz.

### 2.3. Particle generation and counting

Dry clean air (relative humidity < 5 %) is introduced into a custom-designed smoke generator, where the burning of incense sticks generates submicron particles. Then, the particles are entrained by the airflow through the ESP (cross-section area of about 10  $\text{mm}^2$ ). A small amount of the exhaust is connected to a diluter with a controlled additional clean air.

The particle concentration in the diluted sample is measured using an aerosol spectrometer (Pallas Aerosol Technology, Model Wellas-1000, sensor range 0.18 – 40  $\mu\text{m}$ , concentration up to  $10^5$  particles /  $\text{cm}^3$ ). The flow rate inside the ESP is fixed at 1 l/min and measured using a floating ball flow meter (Brooks). Inside the ESP, the particles are electrically charged and collected on the internal surface of the dielectrics. All the experiments are carried out at atmospheric pressure and the room temperature with 1 l/min air flow rate. As a consequence, the transit time (the time for the gas passes through the active volume)

and average gas velocity ranges in the ESP are 0.03 s and 1.67 m/s, respectively.

### 3. Experimental results

#### 3.1. Electrical behavior of the DBD-ESP

##### 3.1.1. Current waveform

Fig. 3 illustrates the typical time evolution of the applied voltage and the discharge current. The waveforms are measured under 10 kV-1 kHz applied voltage. The discharge current waveform is characterized by the presence of numerous current pulses of magnitude up to 600 mA in both positive and negative half-cycles. Thus, the DBD in plane-to-plane configuration at atmospheric pressure operates in a filamentary mode. The current pulses are caused by several micro-discharges crossing the gap at different locations of the dielectric barrier surfaces.

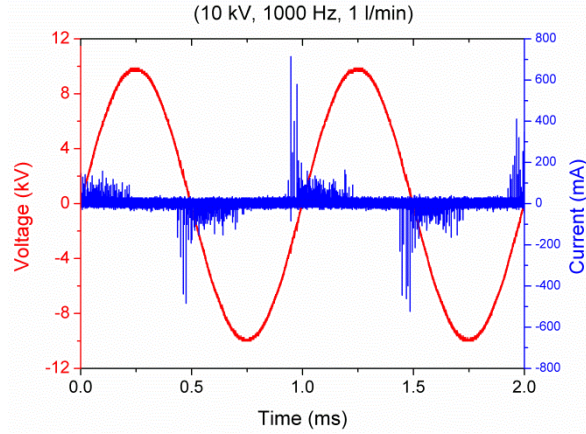


Figure 3. Applied voltage and discharge current waveforms. Conditions:  $V_0=10$  kV,  $f=1000$  Hz, flow rate=1 l/min.

##### 3.1.2. Charge-voltage curve

Fig. 4 shows the evolution of the transferred charge as a function of the applied voltage (so-called Lissajous figure). The Lissajous figure recorded with the filamentary discharge is close to a parallelogram. During the first part of the positive half-cycle (AB), the accumulated charge on the dielectric surface increases with the applied voltage because of the discharge activity in the gap, and it starts to decrease after the maximum voltage (BC) because of the extinction of the discharge (Fig. 3). The negative discharge starts before the negative half-cycle (CD) due to field distortion caused by the charges accumulation on the dielectric surface. The slope of the charge-voltage curve without discharge (BC and EF) represents the total capacitance ( $C_{tot}$ ) of the ESP. Indeed, the total capacitance of the ESP is  $1/C_{tot}=1/C_d+1/C_g$ , where  $C_d$  is the dielectric capacitance and  $C_g$  is the air gap capacitance. In fact, during the discharge (CE and FB), the filaments make a short-circuit in the gap, making the total capacitance bigger and equal to the capacitance of the dielectrics.

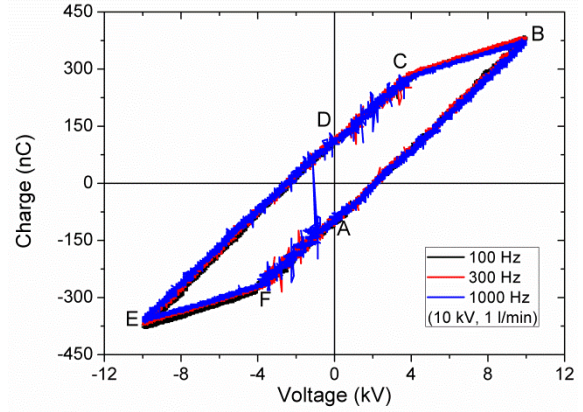


Figure 4. Charge-voltage curve (Lissajous figure). Conditions:  $V_0=10$  kV, flow rate=1 l/min.

##### 3.1.3. Power consumption

The surface of Q-V curve is equivalent to the transferred energy during one cycle. The average power consumption (P) of the discharge is calculated from the measurement of the charge (Q) and the voltage (V) over one cycle (T) using the following equation:

$$P = \frac{1}{T} \oint Q \cdot dV \quad (1)$$

In the previous figure, we notice that the curves corresponds to different frequencies are concentric which means that the frequency doesn't affect the quantity of injected charges or the energy transferred in one cycle. Consequently, as we can see in Fig. 5 which represents the evolution of the average power consumption as a function of the frequency, the power consumption is a quasi-linear function of the frequency. The number of cycles increases with the frequency resulting in higher power consumption.

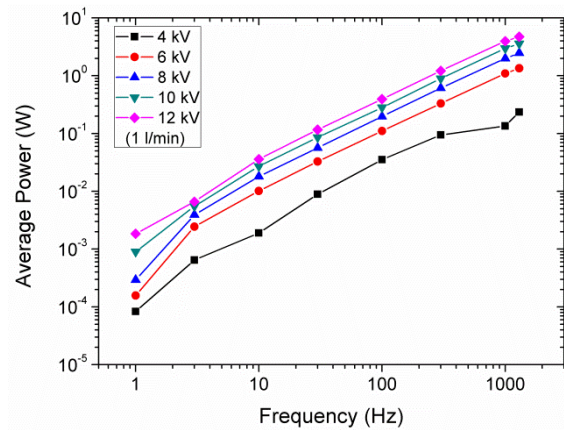


Figure 5. Frequency effect on average power consumption. Conditions: flow rate=1 l/min.

### 3.2. Collection efficiency behavior of the DBD-ESP

#### 3.2.1. Particle size distribution

Fig. 6 shows an example of particle size distribution in the outlet gas with and without the discharge. Thus, the particle sizes under investigation are ranging from 0.18 to 0.7  $\mu\text{m}$ . The highest concentration is obtained for particles with a diameter of about 0.28  $\mu\text{m}$ . When a high voltage (5 kV; 1 kHz in this example) is applied to the planar DBD ESP, the concentration of particles is reduced whatever their size.

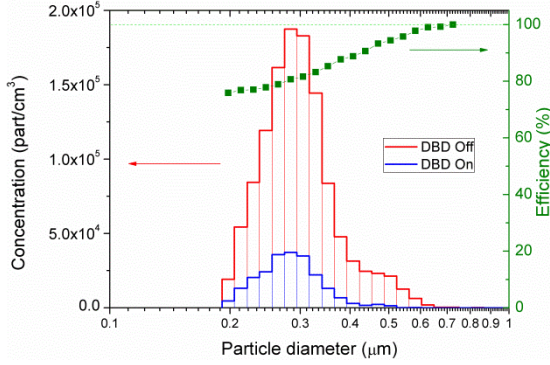


Figure 6. Size distribution of incense particles with and without the filamentary discharge. Conditions:  $V_0=5$  kV,  $f=1000$  Hz, flow rate=1 l/min.

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 ( $\eta$ ) is defined as follows:

$$\eta = 1 - \frac{N_{on}}{N_{off}} \quad (2)$$

With  $N_{on}$  and  $N_{off}$  are the number of particles per cubic centimeter with and without discharge, respectively.

In order to highlight accurate values of collection efficiency, the efficiency of the DBD-ESP is performed using the penetration given ( $P_n$ ) by:

$$P_n = 1 - \eta \quad (3)$$

#### 3.2.2. Frequency effect

In Fig. 7, the particles collection efficiency and penetration are presented as a function of the frequency under 5 kV applied voltage. We can see that the planar DBD-ESP can remove more than 98% of particles in terms of number/volume within the frequency range between 60 Hz and 300 Hz. However, the collection efficiency decreases at low (< 30 Hz) and high (> 600 Hz) frequencies. Similar results have been obtained in other research works [9]. The decrease of the collection efficiency at low

frequencies can be explained by the low charge of aerosol particles [16]. In fact, between two successive half-cycles, the discharge turns off during a time-interval, that is longer than the residence time of the particles inside the plasma reactor, therefore, a fraction of particles are not or not enough charged. At high frequency, the decrease of efficiency is caused by the fast oscillation of the particles between the electrodes, although the particles are highly charged.

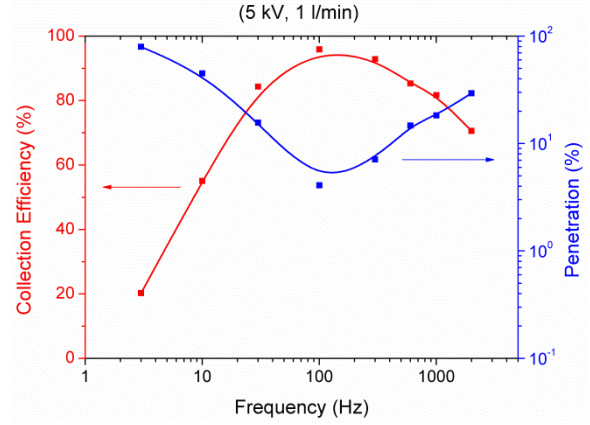


Figure 7. Total collection efficiency and penetration as a function of the frequency. Conditions:  $V_0 = 5$  kV, flow rate= 1 l/min.

#### 3.2.3. Voltage effect

Fig. 8 illustrates the applied voltage effect on particles penetration through the DBD-ESP. As expected, the performance of the DBD-ESP increases with the applied voltage amplitude, especially when it exceeds 4 kV. This is due to the fact that a high voltage magnitude allows a higher injection of ions in the gap; which enhances the particle charging and drift processes.

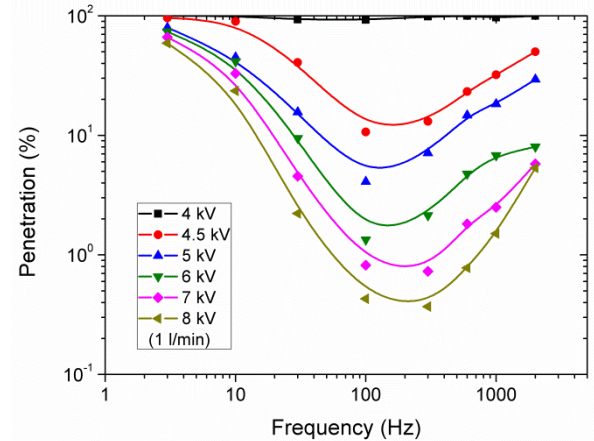


Figure 8. Frequency effect on penetration under various applied voltage values. Conditions: flow rate= 1 l/min.

#### 3.2.4. Particles size effect

Fig. 9 shows the evolution of the penetration as a function of the frequency for particles with different sizes. The experimental conditions are 5 kV of applied voltage and 1 l/min of flow rate. We have always a

high penetration at both and low frequencies but we can see that the penetration decreases with the particle size so consequently the performance of the DBD-ESP increases. This is caused by the fact that big particles are able to acquire more charges due to the field charging mechanism.

We notice also that the collection efficiency of 0.305  $\mu\text{m}$  particles is practically similar to the total collection efficiency because of the high concentration of particles in this size range.

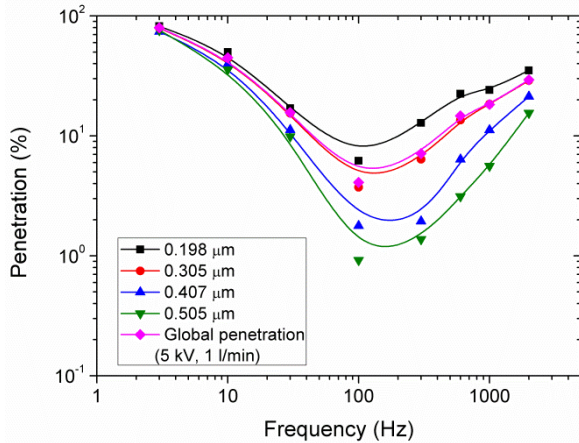


Figure 9. Particles size effect on penetration. Conditions:  $V_0 = 5 \text{ kV}$ , flow rate= 1 l/min.

### 3.2.5. Flow rate effect

Fig. 9 illustrates the evolution of the collection efficiency as a function of the frequency for three flow rates (1, 3 and 5 l/min). As expected, when the flow rate increases the resident time of the particles inside the plasma region in the DBD-ESP reduces, which by the way affects the charging process of particles and then the particles penetration increases.

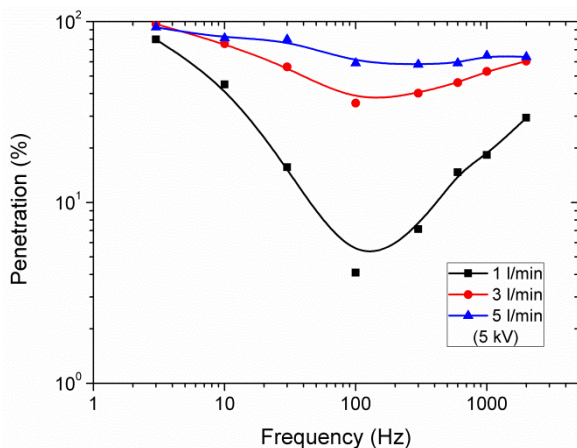


Figure 10. Flow rate effect on particles penetration. Conditions:  $V_0 = 5 \text{ kV}$ .

## 4. Conclusion

The aim of this work was to investigate the effect of the frequency on the electrostatic precipitation of submicron particles using dielectric barrier discharge in plane-to-plane configuration.

After analyzing the discharge current waveform and Lissajous figures, results show that the dielectric barrier discharge has a filamentary mode and the energy transferred in one cycle is the same whatever the frequency.

The experimental results of the particles penetration have shown that the DBD-ESP have a high performance at high applied voltage and with large particles due to the enhancement of the electric field charging process. The planar DBD-ESP is also more efficient at low flow rate such as most electrostatic precipitators. It can reach a high efficiency (98 %) in a certain range of the frequency. However, the collection efficiency decreases at low frequencies because of the low charge on particles which affects negatively their collection, and at high frequencies because of the fast oscillatory motion of particles.

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