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Time-resolved measurements of the electrohydrodynamic phenomena in an electrostatic precipitator using AC dielectric barrier discharges

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Abstract— In this paper, the interaction between a dielectric barrier discharge and submicron particles is investigated experimentally using Laser Doppler Velocimetry (LDV) technique in wire-to-plane configuration. The induced electrohydrodynamic (EHD) phenomena have been studied by time-averaged and time-resolved measurements for different AC high voltage waveforms. The main results indicates that the particle time-averaged velocity increases with the HV frequency whatever the measurement position due to electric wind effect on particles. The time-resolved velocity increases during both positive and negative discharges inducing a strongly non-stationary EHD flow. After the propagation of a streamer, a reduction of the particle number in the measurement volume is observed at low frequency probably due to the pressure wave generated by the streamer.

Keywords — AC-DBD, electrohydrodynamic, electrostatic precipitation, particle velocity, time-resolved LDV measurements

I. INTRODUCTION

Recent studies demonstrate the great potential of dielectric barrier discharge based electrostatic precipitators (DBD-ESPs) energized by a low frequency AC high voltage for the collection of submicrometer particles [1-5]. The frequencies range from a few Hz to several kHz, for voltages up to 30 kV. However, particle charging and drift processes are still not very well understood in particular in the case of filamentary discharges [6].

The goal of the work presented here is to investigate how the DBD interacts with submicron particles in an electrostatic precipitator. Laser Doppler Velocimetry (LDV) technique is used to measure the time-resolved velocity of particles in wire-to-plate geometry supplied by different AC high voltage waveforms, and to compare the electrohydrodynamic phenomena that result in particle precipitation.

II. EXPERIMENTAL SETUP

A. Geometric configuration

The investigation is carried out with a wire-to-plane geometry shown in Fig. 1. The configuration is composed of two electrodes separated by a dielectric barrier (Pyrex, 1 mm thick, 200 mm in length, and 100 mm in width). The active electrode consists of a nickel wire (0.2 mm in diameter). The plane electrode (aluminum tape, 20 mm in length, 20 mm in width and 70 μ m thick) is placed on the lower side of the dielectric barrier and encapsulated. The air gap is fixed at 4.9 mm in all experiments.

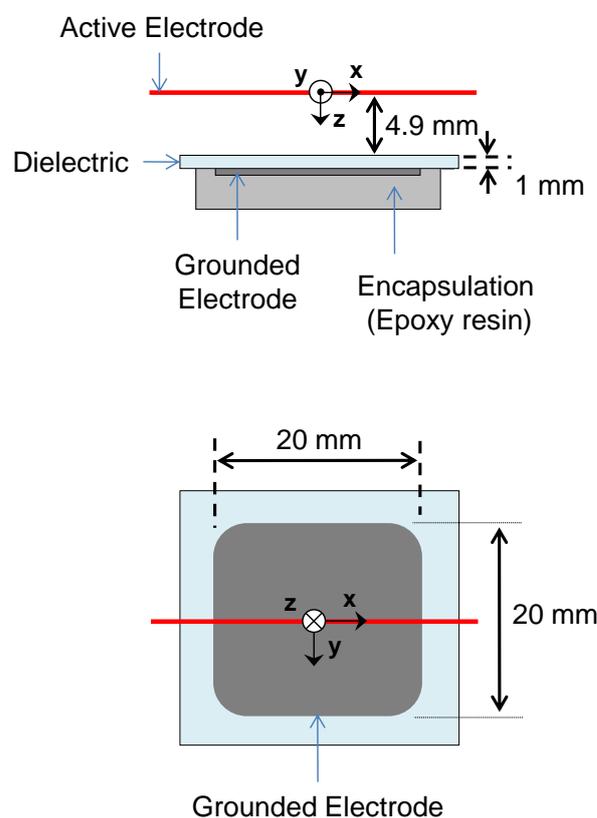


Fig. 1. Top and side views of the wire-to-plane geometry

B. Electrical devices

The power supply system consists of a high voltage power amplifier (Trek, Model PD06035), a function generator (TTI, TG1010), 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, 2 GS/s). To generate the discharge, the wire is connected to the high voltage power supply and the plane

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electrode is grounded. More details about the electrical system can be found in [4].

C. Particle tracking using LDV

Submicron particles, with a mean size of about 0.28 μm , are generated from incense burning and introduced into a closed box made of glass (80 cm \times 40 cm \times 30 cm) in order to examine the non-stationary velocity of particles induced by the discharge in the inter-electrode gap.

The velocity of particles is analyzed experimentally using LDV device as illustrated in Fig. 2. The light source is an Argon-ion laser (Spectra-Physics, 5 W maximum). Within a measurement volume of about 0.1 mm \times 0.5 mm, interferences fringes are generated between two green beams (wavelength of 514.5 nm). When a particle passes through the interference fringes it scatter light periodically, this indicates the particle velocity. The detection device, provided by Dantec, is composed of a photomultiplier connected to a Doppler signal analyzer which calculates the velocity of particles. The acquisition rate is about 10 kHz and about 200 000 bursts are collected for temporal analysis. The whole system can be moved along the x and z axis (Fig. 1). Only Vz component (from the wire toward the grounded electrode) of the particle velocity is considered in this work. Furthermore, $y = 0$ mm in all experiments.

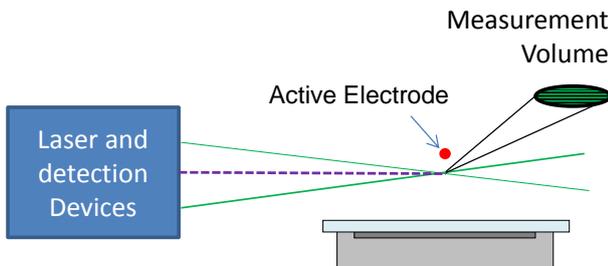


Fig. 2. Schematic illustration of the LDV setup.

III. RESULTS AND DISCUSSION

A. Electrical behavior

Fig. 3(a) shows the typical waveforms of the applied voltage and current in the case of sine waveform without particles in the gap. The current envelope is also recorded (cyan curves). It results from the superposition of the maximal and minimal values of the current during 100 successive periods.

The discharge current includes few current peaks (amplitude up to 500 mA) during the positive half-cycle, while there are numerous current pulses (less than 10 mA) during the negative one. In the positive voltage half-cycle, the discharge is characterized by a streamer regime. The Trichel pulses dominate the negative voltage half-cycle.

Fig. 3(b) shows the typical waveforms of the applied voltage and current in presence of particles. Even if there is some similarities with the previous case, the discharge activity seems to be more intense especially during the negative half-cycle where current pulses magnitude grows up to 250 mA (result not shown in Fig. 3).

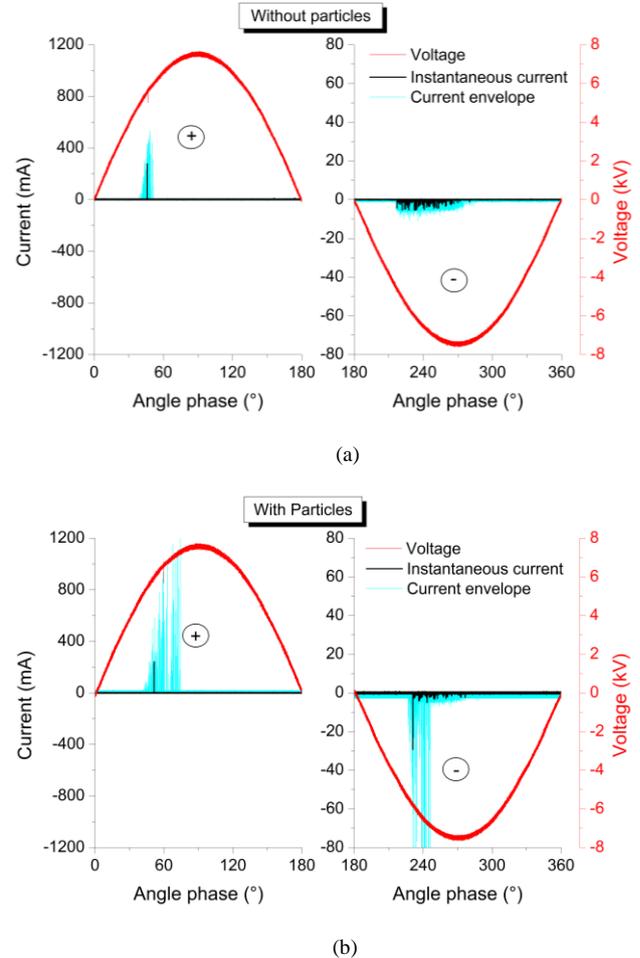
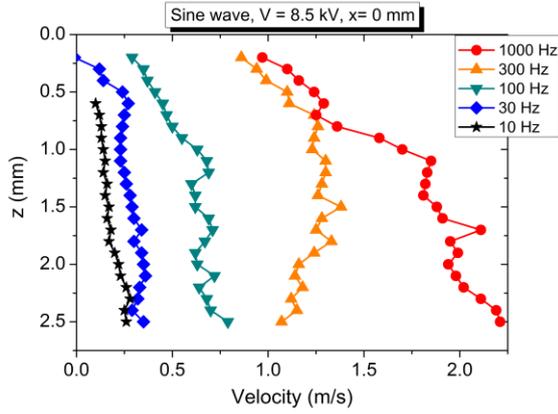


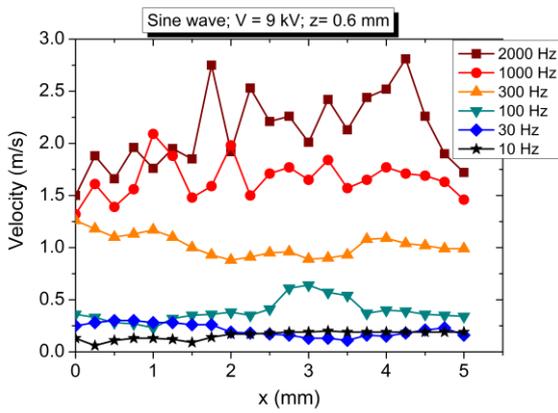
Fig. 3. Typical waveforms of the applied voltage and current (a) without particles, and (b) with particles. Conditions: voltage = 7.5 kV and frequency = 30 Hz.

B. Time-averaged velocity

Fig. 4 illustrates typical examples of time-averaged velocity profiles in the inter-electrode gap for different frequencies ranging from 10 to 2000 Hz. Results show that the particle velocity increases with the frequency whatever the measurement position, which indicates that the particles follow mainly the electric wind produced by the discharge. Furthermore, time-averaged velocity profiles along x-direction are very fluctuating at high frequency (Fig. 4(b)). This is probably due to non-uniform distribution of the discharge along the active electrode.



(a)



(b)

Fig. 4. Time-averaged velocity profiles along (a) z-direction (at $x = 0$ mm) and (b) x-direction (at $z = 0.6$ mm).

C. Time-resolved velocity

The LDV acquisition is not regular in time. A velocity measurement corresponds to the transit of a particle in the measurement volume. Fig. 5 shows typical temporal evolution of particle velocity obtained at $x = 0$ mm and $z = 0.6$ mm. In this case, the sine voltage magnitude is fixed at 9 kV and the frequency at 300 Hz. Thus, a short sequence of about 10 ms corresponds to 3 periods of the applied voltage. The results show that the instantaneous velocity is strongly non-stationary. It varies between 0.5 and 2.5 m/s.

Fig. 6 shows an example of the velocity histogram. There are usually one or more peaks depending on the coordinate of measurement and the high voltage parameters. In Fig. 6, two peaks are visible: one peak at about 1 m/s that corresponds to the minimum velocity in Fig. 5, and a second peak at 2 m/s resulting from the maximal velocity value.

The beginning of the LDV measurement is synchronized with the applied voltage connected to the active electrode. Thus, phase averaging technique can be used to analyze the quasi-periodic EHD phenomena induced by the discharge. The velocity measurements are processed to reconstruct the evolution of the particle

velocity during a period of the applied voltage, as illustrated in Fig. 7. The result is obtained for an acquisition time of about 19.67 seconds, which corresponds to 5900 periods of the applied voltage. It shows that the particles are accelerated during both positive and negative half-cycles. However, an apparent lack of data is observed during the positive half-cycle (angle phase between 60° and 120°).

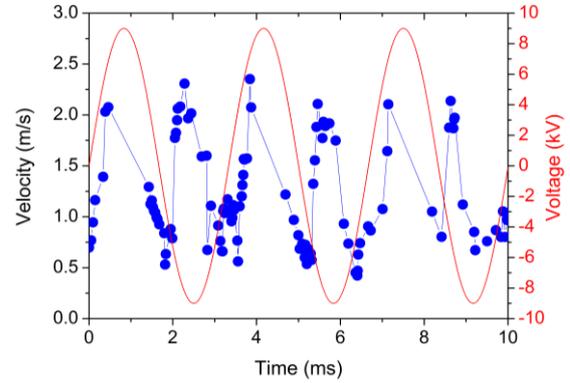


Fig. 5. Typical temporal evolution of the particle velocity. Conditions: voltage = 9 kV, frequency = 300 Hz, $x = 0$ mm and $z = 0.6$ mm.

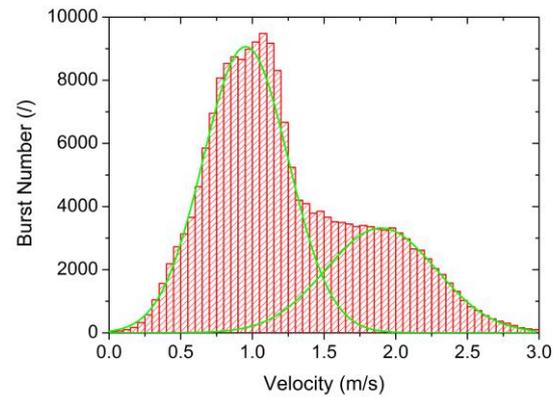


Fig. 6. Typical velocity histogram. Conditions: sine wave, voltage = 9 kV, frequency = 300 Hz, $x = 0$ mm and $z = 0.6$ mm.

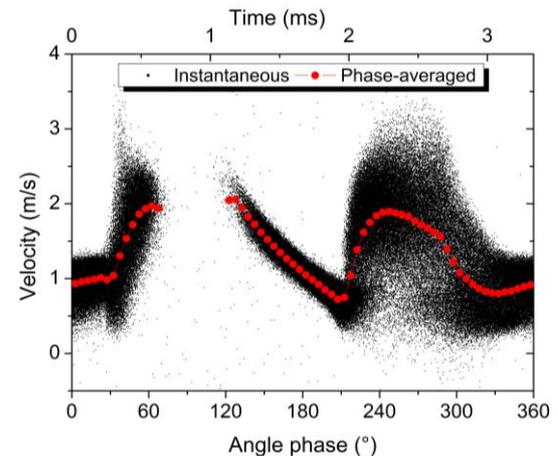


Fig. 7. Phase reconstruction of the time-resolved velocity. Conditions: sine wave, voltage = 9 kV, frequency = 300 Hz, $x = 0$ mm and $z = 0.6$ mm.

D. Particle counting analysis

In order to analyze precisely the origin of the reduction of particles transit in the measurement volume, phase averaging of the burst number is plotted with the discharge current in the case of sine, square and triangular voltages, as illustrated in Fig. 8. In order to reduce the effect of electric wind, only low frequency results (at 30 Hz) are presented in this section. Then, the period is discretized into 72 sub-sets allowing listing the

number of bursts as a function of time (or angle phase). In the case of sine wave (Fig. 8(a)), the typical burst number is about 4000 for each subset without discharge. However, it decreases drastically by more than two orders of magnitude after the streamers that occurs at 60° and then returns to a normal level just before the occurrence of the negative discharges. Similar behavior is observed with square and triangular voltage waves as illustrated in Fig. 8(b) and Fig. 8(c).

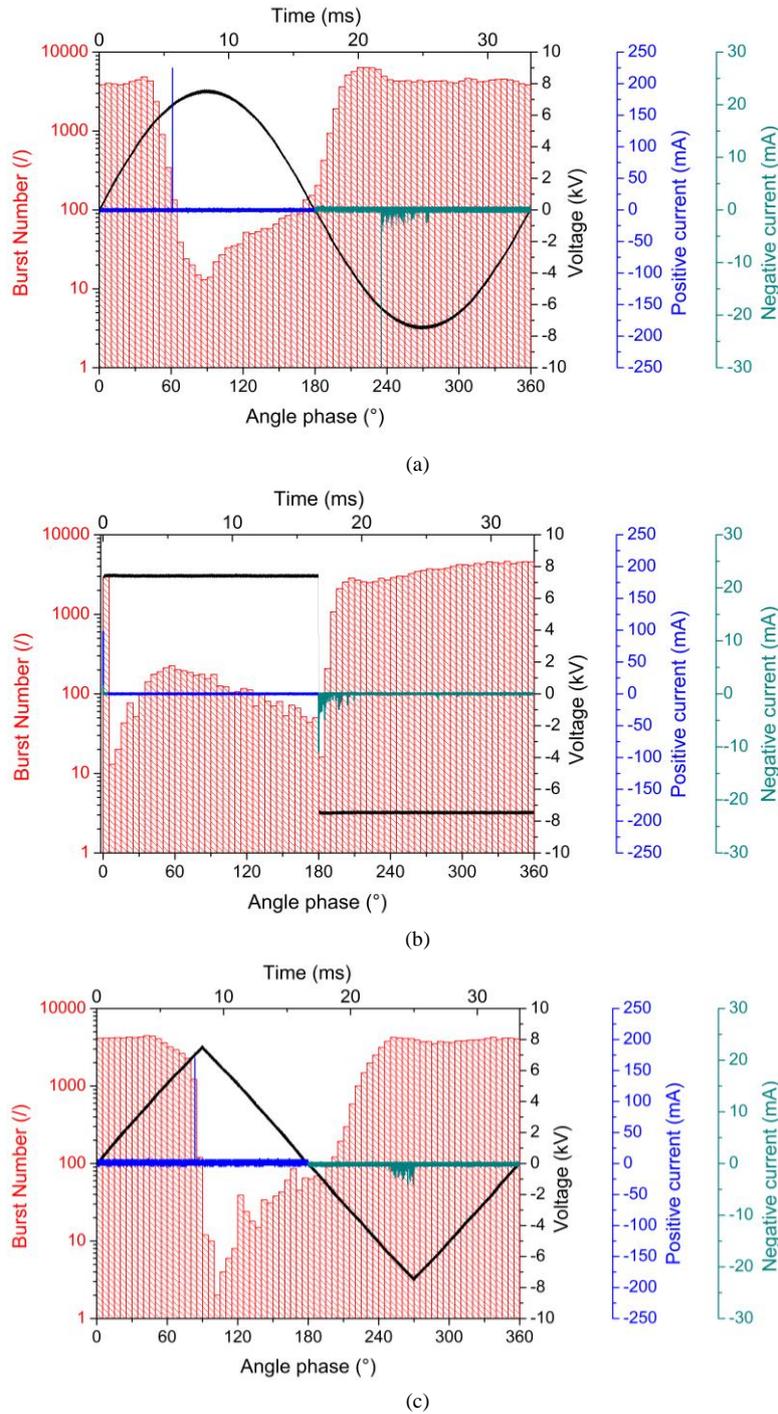


Fig. 8. Bursts number evolution as a function of angle phase in the case of (a) sine wave, (b) square wave and (b) triangular wave. Conditions: voltage = 7.5 kV, frequency = 30 Hz, x= 0 mm and z = 0.6 mm.

The disappearance of particle after the occurrence of streamers is probably due to the pressure wave produced by the streamers as in DBD plasma actuators [7]. Moreover, it seems that particles are electrically charged, and then precipitated by the electric field. Further experiments with time-resolved Particle Image Velocimetry (PIV) associated to Schlieren visualizations should allow us to conclude about the physical mechanisms that induce the local reduction of particle concentration in the inter-electrode gap.

IV. CONCLUSION

In this work, we investigated the interaction between a dielectric barrier discharge and submicron particles using LDV technique in a wire-to-plane configuration. In particular, particle time-resolved velocities have been analyzed for different AC high voltage waveforms. The main results of this experimental study are as follows.

(1) The particle time-averaged velocity increases with the frequency whatever the measurement position, which indicates that the particles follow mainly the electric wind in the inter-electrode gap.

(2) The time-resolved velocity of particle increases during both positive and negative discharges, which induces a strongly non-stationary EHD flow.

(3) After streamer propagation, a reduction of particles is observed. It is probably due to effect of pressure wave generated around the streamer channels and electrostatic precipitation.

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