NANOSECOND PULSED DIELECTRIC BARRIER DISCHARGES APPLIED TO ELECTROSTATIC PRECIPITATION

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ABSTRACT

In this paper, a dielectric barrier discharge based electrostatic precipitator powered by a nanosecond pulsed high voltage is investigated experimentally. The first goal is to characterize the electrical behaviour of the discharge in wire-to-square tube configuration. The second one is to analyse the effect of the voltage pulse polarity on submicrometer particle collection efficiency, before to be compared with AC sine and square voltage waveforms. The main results show that the performance of the ESP is better with the positive pulse voltage due to filamentary discharge regime, even if the voltage pulse duration is short compared to the waveform period.

1. INTRODUCTION

For more than a century, researches on corona discharge electrostatic precipitators (ESPs) have made them more efficient and robust. However, there are still too many phenomena deteriorating their performance such as the: dependence on particle size, the particle re-entrainment and the back corona discharge, among others [1].

Recent studies demonstrate the potential of dielectric barrier discharge electrostatic precipitators (DBD-ESPs) energized by a low frequency alternating high voltage for the collection of submicrometer particles [2-4]. The frequencies range from a few Hz to several kHz, for voltages up to 30 kV. In most cases, the power supply system includes a high voltage linear amplifier with moderate slew rate (less than 1 kV/µs). However, only few studies deal with the use of nanosecond pulsed voltage for the electrostatic precipitation of particles.

In this paper, the effect of the positive and negative pulsed voltage polarities are examined and compared with AC sine and square voltage waveforms. The analysis relates to the electrical characterization of the discharge and the collection efficiency of submicrometer particles in wire-to-square tube ESP configuration.

2. EXPERIMENTAL SETUP

The experimental setup used in this investigation is composed of four main modules (Figure 1): the power supply system and electrical probes, the smoke generator, the particle counting system and the electrostatic precipitator.

Dry clean air is introduced into a custom-designed smoke generator, where the burning of incense sticks generates submicrometer particles. Then, the particles are entrained by the airflow through the ESP under study. The ESP outlet is connected to a diluter with a controlled additional clean air. Finally, the particle concentration in a diluted sample is measured using an aerosol spectrometer (Palas, Model Wellas-1000). For all experiments, the flow rate inside the ESP is fixed at 2 L/min, resulting in a flow velocity of 0.33 m/s.

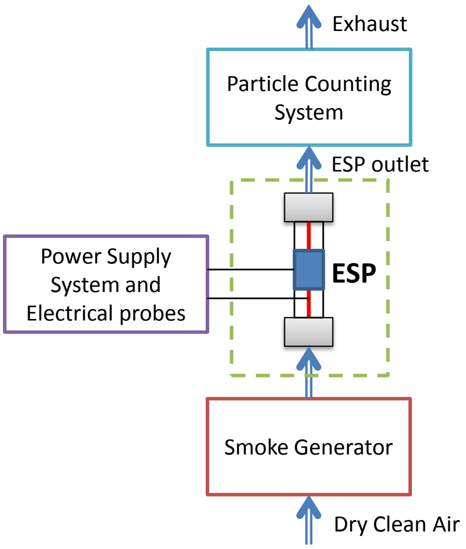


Fig. 1 Schematic illustration of the experimental setup

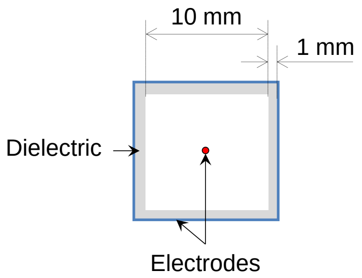


Fig. 2 Cross-view of the DBD-ESP

The analysed particles are ranged from 0.18 to 1 µm with median particle diameter of 0.28 µm. The typical cumulative particle concentration is about 8×10^5 particles/cm^3.

The DBD-ESP (Figure 2) consists of a dielectric square tube (Pyrex, 1 mm thick, 300 mm length, and 10 mm inner ribs) and two electrodes. The active electrode consists of a stainless steel wire (0.2 mm in diameter) aligned at the central axis of the dielectric tube. The collecting electrode (aluminum tape, 20 mm length and 80 µm thick) is placed on the external surface of the glass square tube.

In this study two types of high voltage waveforms are used: AC and nanosecond pulsed waves. For the case of AC wave, 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 external electrode is grounded.

For the case of nanosecond pulsed wave, the high voltage power supply is composed with an HV solid-state pulser (DEI, model PVX-4110), a DC power supply (Matsuda, model 10P30) and a digital pulse generator (Stanford, model DG645). A single pulser can provide a high voltage pulse up to ± 10 kV, whose rise and decay times are about 50 ns. By connecting two pulsers in series-opposition, the potential difference between active and collecting electrodes can reach ± 20 kV. The total current is measured using a fast current transformer (Bergoz, model CT-D1.0) and the potential difference across ESP is measured with twin high voltage probes (LeCroy, model PPE20kV). More details about the experimental setup can be found in [3-5].

3. RESULTS AND DISCUSSION

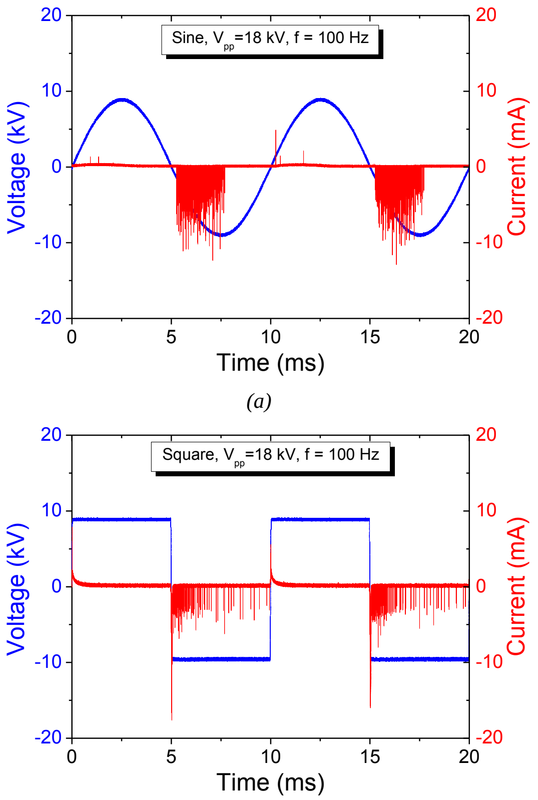
3.1. Current waveforms

3.1.1. AC high voltage

Figure 3a shows a typical time evolution of the applied voltage and the associated current with the standard sine waveform. The peak-to-peak voltage is fixed at 18 kV. The discharge current of the ESP includes only a few current pulses during the positive half-cycle, while there are numerous current peaks during the negative one. In the positive voltage half-cycle, the discharge is characterized by a corona-glow regime. The Trichel pulses dominate the negative voltage half-cycle [3].

Figure 3b shows the time evolution of the applied voltage and the current for a square input waveform. During the positive half-cycle, one can clearly identify the positive corona-glow although the discharge activity is depending on the input waveforms. During the negative half-cycle, the Trichel pulses occur.

The comparison between the square and sine waveforms shows the similarities of the discharge regime. It also appears that the discharge activity duration is longer for the square waveform compared to the sine one where it is clearly less than the period of the signal.



(a)

(b)

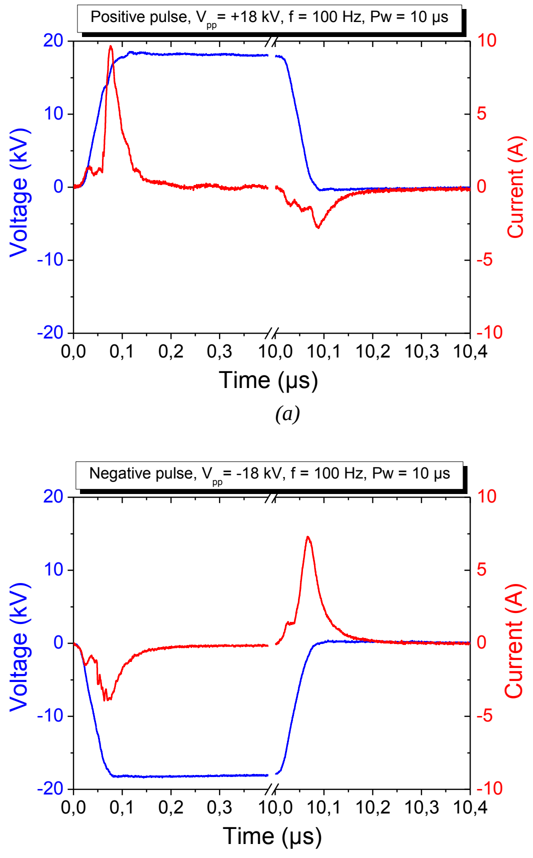
Fig. 3 Time evolution of the applied voltage and discharge current for (a) sine, and (b) square waves

3.1.2. Nanosecond pulsed high voltage

Typical waveforms of the nanosecond pulsed voltage and the associated current are shown in Figure 5 for both positive and negative polarities. During electrical characterization, the ESP is supplied with a voltage pulse of ± 18 kV at a frequency of 100 Hz and a pulse width of 10 µs.

The current waveform shows two peaks well resolved during rise and fall times of the voltage pulse whatever the polarity. No current peak can be observed during the voltage plateau. This is why no data are presented in the range from 0.4 to 10 µs.

The first current peak is due to the deposition of electric charges (with the same polarity than the active electrode) produced by the discharge initiated close to the wire where the electric field is sufficiently intense. During the voltage plateau, the current level decreases rapidly and the discharge is then in its silent period. When the potential difference between the wire and the charged internal tube surface is one more time sufficient, a new discharge propagates in the gap; this is the second discharge which takes place during the second transition of the voltage. Hence, the second current peak appears.



(a)

(b)

Fig. 4 Typical current waveforms for nanosecond pulsed voltage for (a) positive, and (b) negative polarities

The shape of the current peaks is nearly similar; however the discharge regimes associated to each one are completely different. Generally, a positive transition of the voltage pulse favours the formation of streamers-like regime, whereas the negative transition is associated with a corona-glow regime [6].

3.2. Collection efficiency

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

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

where N_{ON} and N_{OFF} are the number of particles per cm^3 for overall size-classes with and without plasma, respectively, which are measured at the outlet of the ESP.

Figure 5 shows the effect of the voltage waveform on the evolution of the collection efficiency as a function of the average power consumption at fixed frequency (100 Hz). The performance of the ESP is better at higher power consumption, except the case of positive pulse at high voltages.

In the case of AC voltage, the square wave offers better performance than the sine wave since the discharge activity duration is longer with a strong electric field in the two half-cycles.

In the case of negative nanosecond pulsed voltage, the electrostatic precipitation is non-effective, because the pulse duration (about 10 µs) is negligible compared to the signal period (10 ms). Consequently, the drift process of the charged particle is affected by the absence of an external electric field during the most part of the period.

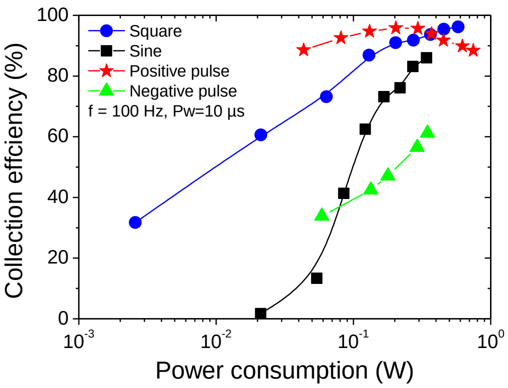


Fig. 5 Evolution of the collection efficiency as a function of the power consumption

Despite a pulse width which is only 1/1000 of the period and a discharge that develops only over a period of about 1/100 of the pulse (this means that the discharge is activated during only 0.001% of time), the performance of a positive pulse excitation can be better than the square waveform one. This indicates that the particle charging and drift processes operate in a completely different mode compared with the other cases.

In fact, with AC voltage, the particles are charged by the ions produced near the wire and driven by the Coulomb forces due to the electric field present in the inter-electrode gap. The same scenario is valid with negative nanosecond pulsed voltage excitation. The discharge, occurring near the wire during the negative transition of the voltage, produces the necessary negative ions for the particle charging process. Then, an extended voltage plateau is required for the electrostatic precipitation of the particle.

In the case of positive pulse, the discharge operates in a filamentary mode during the positive transition of the voltage. Thus, there are two possible scenarios for electrostatic precipitation of submicrometer particles with filamentary discharges [7]. Particles are charged by the positive ions remaining in the gap after filament propagation, then drift slowly toward the collecting electrode during the voltage plateau. Or else, particles are collected during filament propagation, probably due to the contribution of electrons in the charging process or the effect of the generated pressure wave [7]. Since the pulse width is too short compared to the period, the second scenario seems to be the most plausible.

4. CONCLUSION

In this work, we investigated the collection of submicrometer particles using DBD-ESP powered by nanosecond pulsed high voltage. The first goal was to characterize the electrical behaviour of the discharge in wire-to-square tube configuration. The second one was to analyse the effect of the voltage pulse polarity on particle collection, before to be compared with AC sine and square voltage waveforms. The main results of this experimental investigation are as follows.

(1) For both positive and negative pulse voltages, the current waveforms show the existence of two discharges during both rising and falling periods of the voltage.

(2) The performance of the ESP is better with the positive pulse voltage compared to the negative one and the AC voltage waveforms, which is due to filamentary discharge regime, even if the voltage pulse duration is short compared to the period (0.001% of time).

Further investigations are necessary to clearly elucidate the mechanisms of interaction between ultrafine particles and streamers during their propagation.

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