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Effect of relative humidity on current–voltage characteristics of an electrostatic precipitator

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ABSTRACT

This paper aims at characterizing the behavior of dc corona discharge in wire-to-plane electrostatic precipitators (ESPs) as influenced by the relative humidity (RH) of the inlet air. The current–voltage characteristics and time evolution of the current are analyzed. Experimental results show that discharge current is strongly affected by the RH level of the inlet air. For instance, the time-averaged current is lower at higher RH for a given voltage, except when RH = 99%. Time evolution of the discharge current is affected by the humidity especially in the case of negative corona.

1. Introduction

Corona discharge, as applied to Electrostatic Precipitators (ESPs), is a gas discharge phenomenon associated with the ionization of gas molecules by high-energy electrons in a region of high intensity electric field. The process of corona generation in the air at atmospheric conditions requires a non uniform electrical field, which can be obtained by the use of a small diameter wire electrode, energized from a high-voltage supply, and a metallic plate or cylinder, connected to the ground, which is designated as collecting electrode. Industrial ESPs are used with success to reduce the emissions of smoke, fumes and dust, playing an important role to maintain a clean environment and to improve the air quality [1–4]. In terms of mass/volume, the penetration of particles through an industrial ESP can be lower that 1% [2]. In practice, in all these systems particles are charged by means of the ions produced by a DC corona discharge. The electrically charged particles are then driven by the electric field forces towards the collecting electrodes. Their migration is also influenced by the viscous forces associated to the fluid flow and the ionic wind [5–8]. The wet ESP operates on the same principles as the dry ESP; the major difference is that the charged particles are removed from the collecting electrodes by a flushing liquid (usually water), instead of mechanical rapping [9]. Wet ESPs are the solution of choice in the case of humid gases, submicron particles, as well as for controlling the emission of sticky or low electrical resistivity particles [10].

In such systems, the knowledge of the inlet air relative humidity (RH) effect on DC corona discharge behavior is of crucial importance. Some aspects of this effect require further investigations in order to validate a realistic mathematical model of the physical phenomena, as an essential step towards the accurate numerical simulation of the electrostatic precipitation process. The main objective of this investigation is to analyze the effect of the inlet air RH, which can vary from 10% up to saturated conditions, on both positive and negative DC corona discharges employed in wire-to-plane ESPs. In particular, the current–voltage characteristics and time evolution of current are analyzed and discussed.

2. Experimental setup

The schematic representations of the wire-to-plane ESPs used in this investigation are shown in Fig. 1. The collecting electrodes of these ESPs consist of two parallel stainless steel plates, 200 mm-length and 100 mm-width in *x*-direction and *z*-direction, respectively. These two-grounded electrodes are distanced at 100 mm from each other. The high voltage electrodes consist of stainless steel wires (0.2 mm-diameter) parallel to *z*-axis midway between the grounded electrodes. In the first ESP (called 1W-ESP, Fig. 1a), only one wire is connected to the high voltage. The second configuration (called 3W-ESP, Fig. 1b) uses 3 similar wires to create

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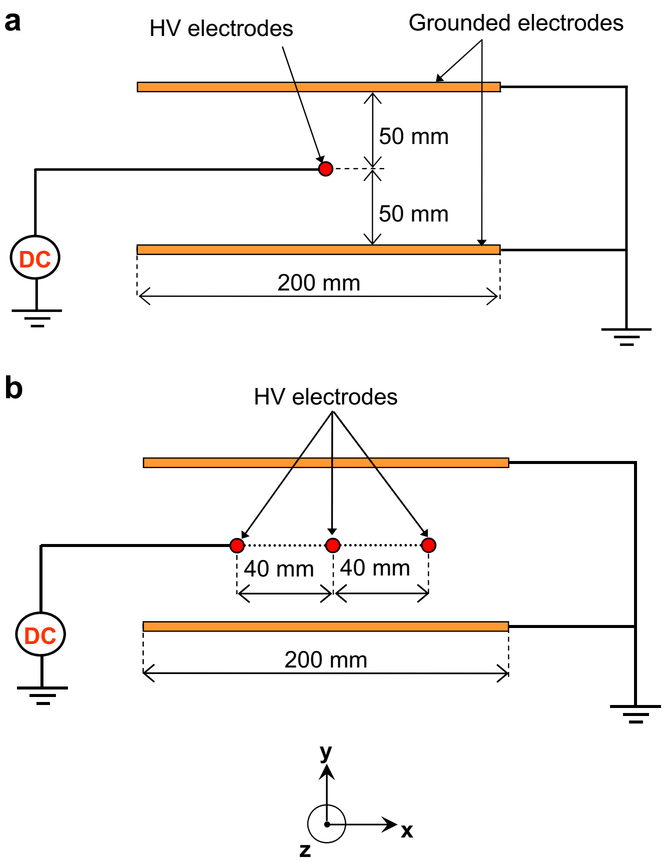

Fig. 1. Laboratory ESP configurations: (a) 1W-ESP, and (b) 3W-ESP.

the corona discharges. The distance between two successive wires is set at 40 mm.

In this study both positive and negative DC high voltage polarities are used. The DC high voltage is provided with an accuracy of 0.1 kV by a reversible power supply (SPELLMAN SL 150, ±40 kV; ±3.75 mA), which is protected by a ballast resistor of 10 kΩ. The time-averaged current is measured through a digital multimeter (METERMAN 37 XR, accuracy ≈1 μA). The time evolution of the discharge current is monitored using a shunt resistor of 100 Ω and a digital oscilloscope (Lecroy 424, 200 MHz, 2 GS/s).

As shown in Fig. 2, the experiments are carried out inside a closed cylindrical vessel (glass, 500 mm-high, and 250 mm-diameter) filled with clean air. Since the effect of temperature and pressure on the electrical behavior of a corona discharge has been examined extensively in the literature, the effect of the relative humidity of the inlet air ($0 < RH < 100\%$) is the only parameter taking into account in this work. During each experiment, the temperature (T) and the pressure (P) inside the test chamber are controlled ($T = 22 \pm 1$ °C, $P = 1 \times 10^5 \pm 7 \times 10^2$ Pa).

The relative humidity of the ambient air varies between 45 and 70%. It was reduced by introducing a dry clean air ($RH < 5\%$) coming from a compressed air network system, or increased by adding water vapor resulting from heated water after a period of relaxation in a container (during 15 min). The RH of the air inside the test chamber is monitored with a dedicated sensor (Hygrometer SR-1364, accuracy ≈ 3%).

Each current–voltage characteristic represents the average of five series of measurements. Between any two measurements, the gas is entirely renewed and the electrode surfaces are cleaned.

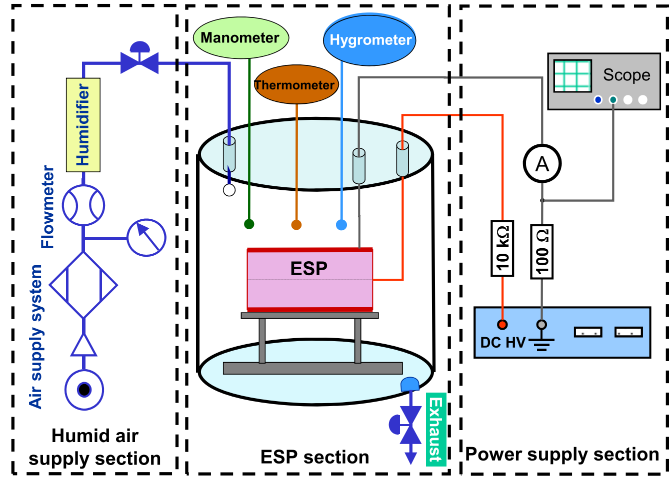

Fig. 2. Experimental setup.

3. Results and discussion

In the following sections, the effect of air RH on the current–voltage characteristics of the two electrode configurations is discussed.

3.1. Current–voltage characteristics

Fig. 3 shows the current–voltage characteristics in the case of 1W-ESP and 3W-ESP for both high voltage polarities. The right side scale indicates to the current density at the collecting electrodes.

The discharge behavior is similar in both ESPs. The discharge current increases with the applied voltage when it exceeds the corona onset voltage until gas breakdown. At a given voltage, the discharge current is higher with the negative polarity, which is explained by the difference between the apparent mobility of negative charge carriers compared to positive ones [11] and [12].

Whatever the polarity, the discharge current increases with the number of HV electrodes for a given voltage. However, the corona current generated by three wires is lower than three times the value measured with one wire ($I_{1\ wire} < I_{3\ wires} < 3 \times I_{1\ wire}$). This is due to the electric field interaction between two successive high voltage wires. In fact, the distance between the wires is lower than the interelectrode gap.

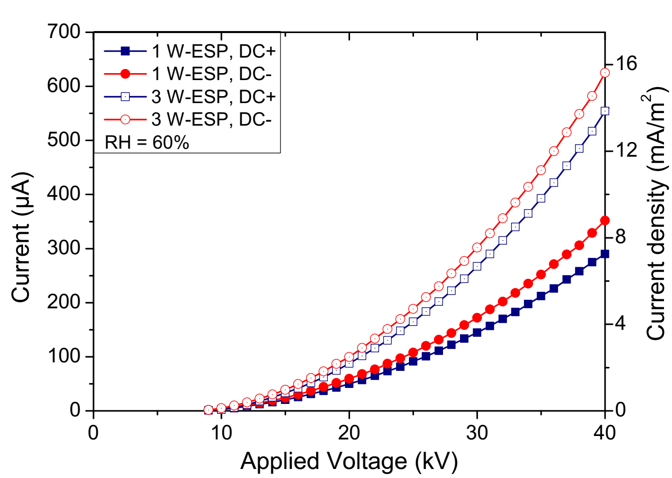

Fig. 3. Current-voltage characteristics of 1W-ESP and 3W-ESP for RH = 60%.

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3.2. RH effect on current–voltage characteristics

Fig. 4 shows the current–voltage characteristics at different relative humidity values in the case of 1W-ESP. The log-linear representation is adopted here in order to show the early stage of the corona discharge.

Depending on the applied voltage, RH effect on the discharge current is different. At a given low voltage, during the early stage of corona discharge, the current increases with RH due to the electric conductivity enhancement.

At higher applied voltage, RH effect is more complex. Except at RH = 99%, current level is lower at higher RH. This effect is due to the decreases of apparent mobility of ions, resulting from their combination with water molecules at high RH.

The time-averaged discharge current (I) is a non-linear function of the applied voltage (V). Although the corona discharge is a complex phenomenon, the relationship between the current and the voltage can be expressed by a simple formula developed theoretically for the case of wire-to-cylinder configuration [13] and [14], and derived by assuming low currents for the case of wire-to-plane configuration by P. Cooperman [15]:

$$I = C \cdot V \cdot (V - V_o) \qquad (1)$$

where V_o is the corona onset voltage and C is a constant that depends on the electrode configuration and the mobility of charge carriers.

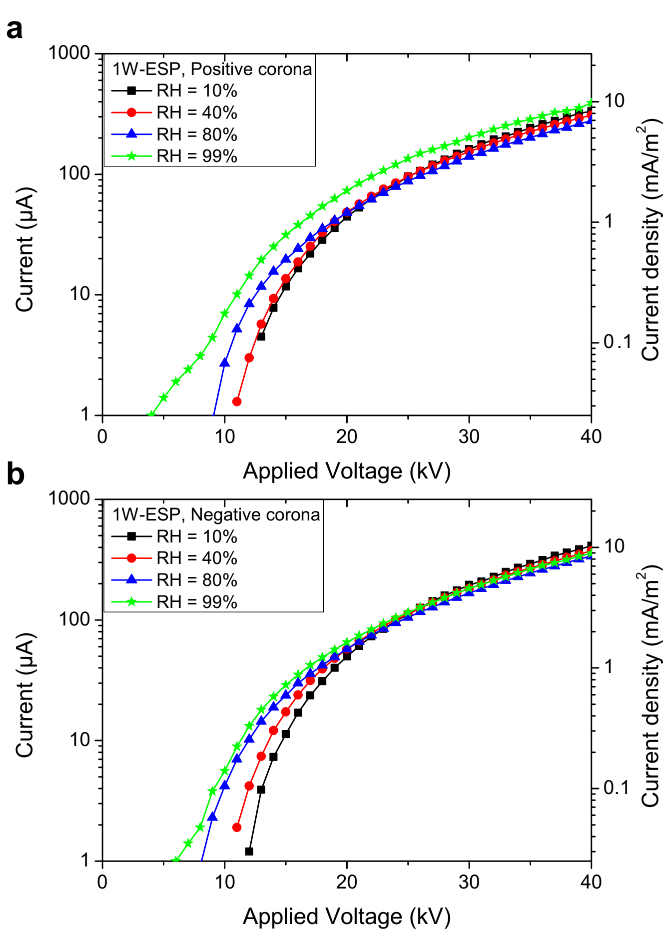

Fig. 4. Effect of relative humidity on current–voltage characteristics in case of 1W-ESP: (a) positive corona, and (b) negative corona.

Obviously, more developed formulas can be found in the literature, especially the one proposed by G. Cooperman in order to take into account the high current range [16].

In Fig. 5 and Fig. 6, V_o and C are represented as functions of RH for both high voltage polarities and both ESP configurations. The results are obtained from fitting the experimental data with the previous equation.

The corona onset voltage is higher in the case of 3W-ESP and especially for negative polarity. Whatever the case, V_o decreases with the relative humidity with two particular transitions in the ranges 30 < RH < 60% and 80 < RH < 100%.

The critical electric field strength (E_o) for the corona onset is given by the Peeks's formula [17]:

$$E_o = A \cdot \delta + B \cdot \sqrt{\frac{\delta}{r}} \qquad (2)$$

where A and B are empirical constants, r is the wire radius, and δ is the relative air density.

Fig. 6 shows that Peek's formula is only applicable if constants A and B are variable as A(RH) and B(RH).

The constant C, which is proportional to the apparent mobility of the charge carriers, is lower in the case of positive polarity. Furthermore, it seems that the apparent mobility decreases with the relative humidity in the range 10 < RH < 80% whatever the case, which confirms the observation noted in the previous section. In addition, C increases for very high relative humidity (RH = 99%), which can be explained by the gas/liquid phase transition inducing the formation of ultra-fine aerosols of water. As these aerosols reduce the probability of the production of heavy ions, the apparent mobility increases.

3.3. RH effect on the time evolution of the current

Typical time evolution of the discharge current is illustrated in Fig. 7 and Fig. 8 for different time-averaged current values (±50 and ±150 μA) in the case of 1W-ESP. The signals are recorded for two different relative humidity values (10 and 80%).

Whatever the humidity level, the time evolution of the negative discharge current presents a strong negative pulse component (Fig. 7). These Trichel pulses are very short and quite regular [18].

As expected, the frequency of the pulses increases with increasing the time-averaged current. The RH clearly affects the negative current pulse magnitude and duration. In fact, they become

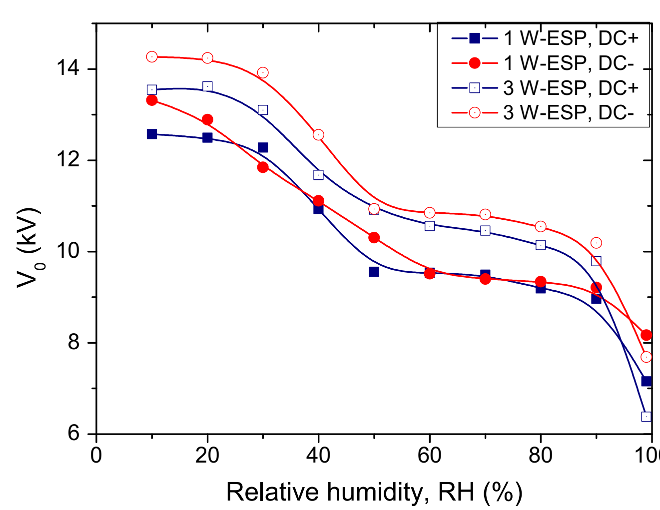

Fig. 5. Variation of corona onset voltage with relative humidity.

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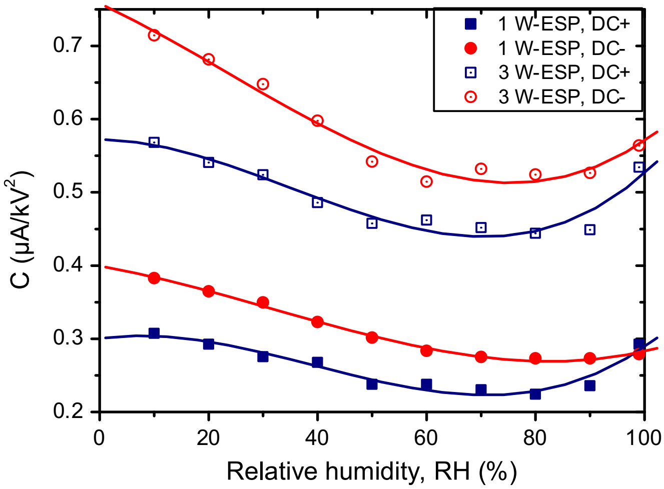

Fig. 6. Variation of C-constant with relative humidity.

intense and shorter with increasing humidity, which means that a big amount of charge carriers are collected on the electrodes during a very short time following the Trichel pulse ignition. This can be explained by a narrow distribution of the apparent mobility at high RH.

With the positive polarity (Fig. 8), only small changes in the time evolution of the current are recorded for low time-averaged current

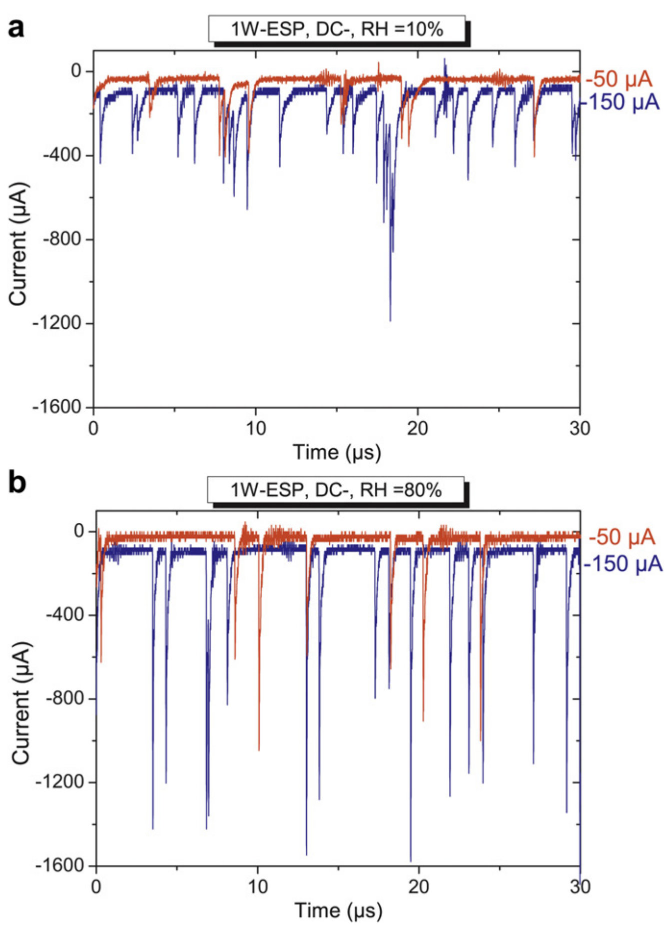

Fig. 7. Time evolution of the negative discharge current in case of 1W-ESP for (a) RH = 10% and (b) RH = 80%.

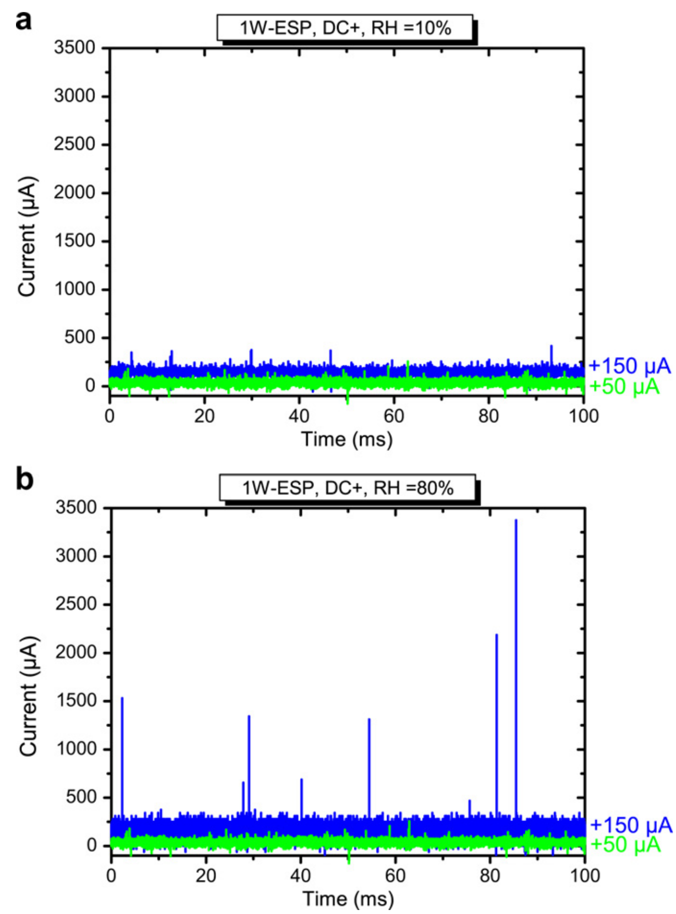

Fig. 8. Time evolution of the positive discharge current in case of 1W-ESP for (a) RH = 10% and (b) RH = 80%.

(I = +50 μA). When the current is increased, for instance I = +150 μA, a streamer-like discharge can be observed at high humidity. The current peaks associated with this regime are not regularly distributed in time. Unlike the negative corona, the positive corona can change the discharge regime with varying the RH.

4. Conclusion

In this paper, the effect of relative humidity on the current–voltage characteristics in wire-to-plane ESP has been investigated experimentally. The measurements have been carried out inside a closed vessel in which the RH can vary from 10% up to saturated conditions.

For otherwise standard atmospheric conditions of pressure and temperature, the magnitude and the time evolution of the corona current are strongly affected by the RH level. Thus, the time-averaged current is lower at higher relative humidity, except when RH = 99%. Corona onset voltage, which is higher with three wires construction, decreases with increasing the RH.

The constant C, representing the apparent mobility of the charge carriers, decreases first with the relative humidity (in the range 10–80%) because the additional mass of ions reduces their mobility. Then, the mobility increases with relative humidity for RH = 99%, which is probably due to the formation of ultra-fine aerosols of water going together with the disappearance of heavy ions.

Time evolution of the discharge current is also affected by the RH especially in the case of negative corona. Thus, the magnitude of Trichel pulses increases with increasing the RH.

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Research is in progress on the RH effects on the collection efficiency of ESPs.

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