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Experimental modelling of wire-to-multicylinder Electrostatic Precipitator

***Abstract**. The efficiency of electrostatic filters depends mainly on the value of the applied voltage and the distribution of the electric field. However, increasing the values of the applied voltage is associated with the increase of the energy consumption resulting in obvious price increase. This paper presents other method of achieving highest efficiency of dust removal. A new geometry arrangement of electrostatic precipitator is investigated experimentally using incense particles in DC corona discharge. An efficiency of 100 % is reached at an applied voltage of 9 kV.*

***Streszczenie.** Analizowano praće filtra elektrostatycznego, a głównie zależność jego skuteczności od przyłożonego napięcia i rozkładu pola elektrostatycznego. Poprawę skuteczności usuwania kurzu osiągnięto prze optymalizację geometrii. (**Eksperymentalne modelowanie elektrostatycznego urządzenia do wytrącania kurzu**)*

Keywords: Electrostatic Precipitators, energy consumption, DC corona discharge, geometry arrangement.
Słowa kluczowe: separator elektrostatyczny, pole elektrostatyczne, wyładowanie DC

Introduction

Most of the processes in manufacturing industrial facilities are accompanied by dust generation and emission phenomena unfavourably affecting ambient environment. Submicron dust particles, which can contain traces of toxic elements, float relatively long in the atmosphere and can easily penetrate into human respiratory system. Consequently, new standards (e.g. The International Standard ISO 13271:2012 and The U.S. National Ambient Air Quality Standards 40 C.F.R) have been introduced in many countries to limit the emission of fine particles [1, 2].

Numerous types of filters with diversified structure have been developed. The range of filters encompasses mechanical filters (e.g. cyclones, fabric and bag filters), dry and wet filters as well as electrostatic filters. Electrostatic precipitation is a technique to remove suspended particles, e.g. dust and smoke, in a gas using electrostatic force acting on a charged particle, minimally impeding the flow of gases through the unit [3, 4].

Electrostatic precipitator (ESP) has large advantages over other particulate control devices: a lower operating cost, because of its low corona power and low power needed in its lower due to a low pressure drop; a high collection performance (99 % - 99.9 %) even for submicron particles(0.3 µm or smaller) ; and ease of maintenance thanks to the simplicity of design. In particular, its low energy consumption has a great importance in view of the current concern in energy saving [5].

Corona discharge is a gas discharge generated in a region close to a high-potential electrode with a small curvature radius. This phenomenon is used in electrostatic precipitators to clean contaminated air from dust particles [6].

The electrostatic precipitation process is associated with the following mechanisms. The high voltage applied to emission electrodes causes corona discharge. As a result of free electrons emission, gas particles within corona range are turned into negative ions. Then, under the influence of electric field, charged gas particles are moving to electrodes with opposite polarity [1].

The configuration of the electrode system of an ESP and the distribution of the electric field have a strong influence on the charging process of the particles and eventually on the collection effinciency [7, 8, 9], as it was shown in many recent studies [10, 11]. However to obtain maximum electric field for particle charging process, it is important to apply the maximum voltage between ESP electrodes, which leads to high energy consumption [12].

The main objective of this paper is to study experimentally a novel ESP design, which is able to reduce the energy consumption and to increase the collection efficiency.

The structure of the electrofilter described in the present paper is based on the use of wire to multi-cylinders ESP geometry. This ESP configuration was designed to increase the electric field inside the ESP and to reduce the total corona discharge.

In the first part of this paper, the experimental setup is described. Then, results concerning the current-voltage characteristics for both positive and negative polarities are measured with and without the presence of particles. Then, the energy consumption and collection efficiency of smoke particles is investigated using an aerosol spectrometer that measures the particle size distribution at the ESP outlet. Finally, conclusions are summarized.

Experimental setup

The measurements of the I-V characteristics and the particle collection efficiency of the ESP have been carried out using an experimental bench that is divided into four parts: the electrostatic precipitator section, power supply unit, the particle supply section and the particle detection instrumentation. The complete experimental bench is illustrated in Fig. 1.

Electrostatic precipitator section

The schematic representation of the wire-to-multi-cylinder ESP used in this investigation is shown in Fig. 2.

The designed ESP includes an iron wire electrode (1) (0.25 mm diameter and 520 mm length) and five grounded cylinder electrodes. The wire electrode is supplied with a high voltage power supply to produce a corona discharge. The collecting unit has two types of cylinder electrodes: interior electrodes made of aluminium (2 mm thick) placed one over the other with 20 mm spacing each two have the same height (the two cylinders on the sides (2) & (3) have a height of 85 mm and the two ones in the middle (4) & (5) have a height of 45 mm). The second type of cylinders is the main grounded electrode (6) made of stainless steel (100 mm diameter, 245 mm length and 1 mm thick); the main and the interior cylinders are coaxial with the wire electrode. The distance between the interior and the exterior cylinder electrodes is 20 mm.

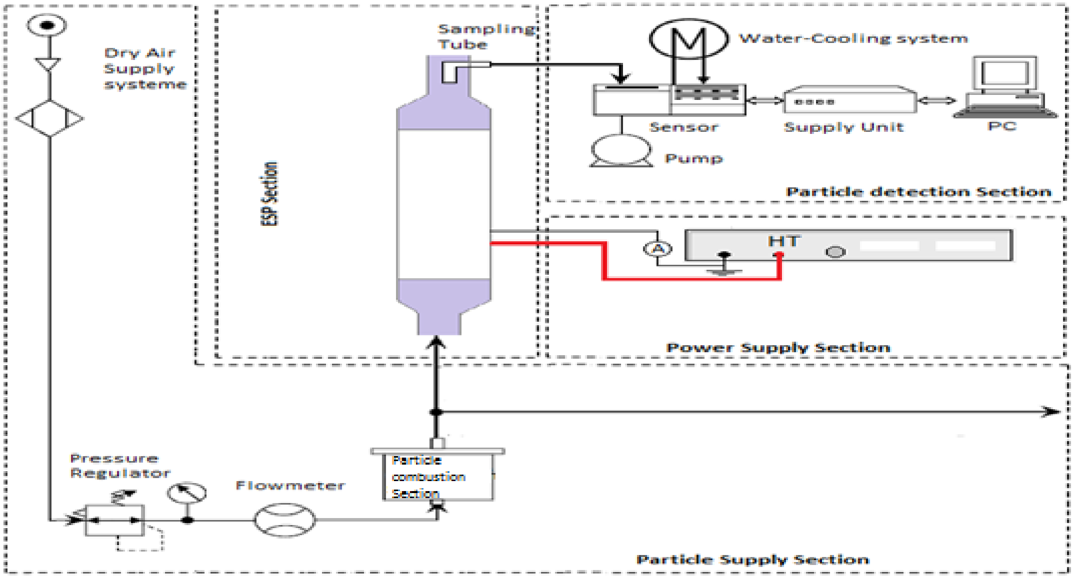

Fig.1. The experimental setup.

Power supply section

The DC high voltage is provided by two power supplies for both positive and negative polarities (Spellman SL 150, ±40 kV, ±3.75 mA). The time-averaged current is measured using a digital multimeter.

Particle supply section

The incense particles, That consist of gaseous pollutants(carbon monoxide (CO), nitrogen oxides (NOx), acid sulfides (SOx), and volatile organic compounds (VOCs)) and solid and liquid aerosols (containing toxic metals), are introduced into the ESP after burning incense sticks in air in a "home-made" smoke generator. In fact, clean air is dried with CaSO4 desiccant (relative humidity < 5%) and mixed with the incense smoke before the introduction into the ESP.

Particle detection section

In order to calculate the collection efficiency of the ESP, the particle concentration in the exhaust gas sample is measured using an aerosol spectrometer (Pallas, Model Wellas-1000, sensor range of 0.18 – 40.00 µm, concentration up to 10^5 particles/cm^3). The counting technique is based on the use of a white light source. A small measurement volume defined optically is illuminated with white light to analyse the scattered light and determine the number and size of particles. The counting system includes four main organs: the optical assemble the electronic circuitry, the pump unit and the cooling device [13].

Clean, dry air from the compressed air system is introduced into the smoke generator in which the burning of incense sticks generates submicron particles; the resulting gaseous mixture is then introduced into the ESP to be tested. Only part of the gas is taken from the outlet of the ESP to be analysed by the aerosol spectrometer. In order to analyse the effect of the ground electrodes on the ESP performance, all the experiments were carried out for three cases:

- All cylinders are grounded;
- Exterior cylinders are grounded;
- Only Interior cylinder is grounded;

The air flow velocity has been fixed at 2.5 m/s. All the experiments are conducted in normal atmospheric conditions of temperature and pressure (T = 24°C, RH = 54 %).

Results and discussion

Electrical characteristics

Fig. 3 shows the current-voltage characteristics of the ESP for both high voltage polarities without the presence of particles.

Obviously, the discharge current increase gradually with the applied voltage when it exceeds the corona onset voltage until the breakdown of the gas inside the ESP [8].

The averaged discharge current (I) is a non-linear function of the applied voltage (V). The relationship between the current and the voltage can be expressed by a simple formula developed theoretically for the case of symmetrical wire-to-cylinder and wire-to-plane configurations [14]:

$$I = CV\left(V - V_s\right) \quad (1)$$

where: I – discharge current, V – the applied voltage, V_s – the corona onset voltage, C – constant that depends on the electrode configuration, temperature, the pressure, and the gas composition, among other parameters.

Fig.2. The ESP geometry

According to Dupuy [15], for a wire-to-cylinder geometry the constant C can be expressed as:

$$C = \frac{8\pi\eta\varepsilon_0}{r_c \ln\left(\frac{r_c}{r_w}\right)} \quad (2)$$

where: η – the mobility of charge carriers, ε_0 – air permittivity, r_c – the cylinder radius, r_w – the wire radius.

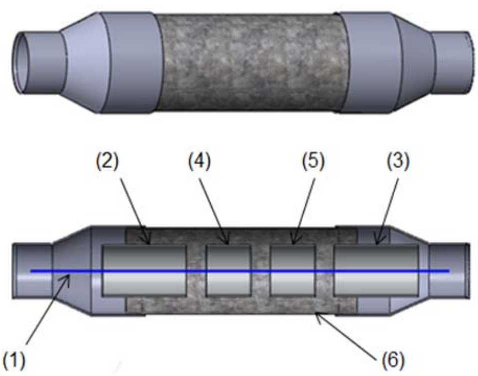

Fig.2. The ESP geometry

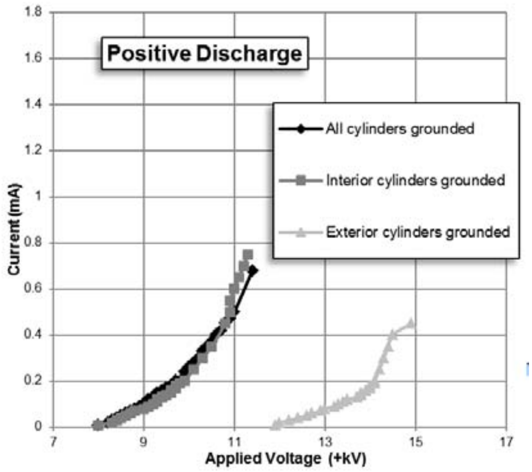

Fig.3.a. Current-voltage characteristics for positive corona discharges without particles.

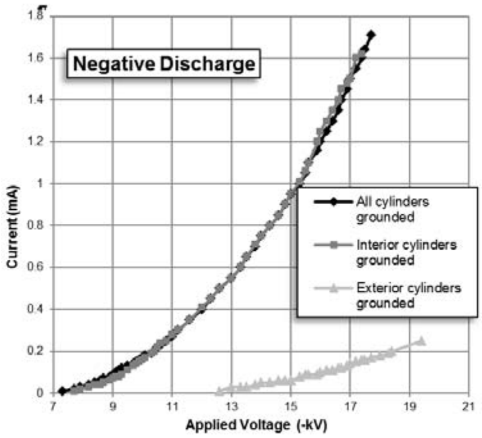

Fig.3.b. Current-voltage characteristics for negative corona discharges without particles.

The effect of polarity can also be identified. At a given voltage, the onset voltage of the negative corona discharge is lower than the positive discharge ($V_{s-} < V_{s+}$). In addition, the discharge current is higher with negative polarity for a given voltage. This could be explained by the difference between the apparent mobility of negative charge carriers compared to positive ones [16].

As reported in the past, the negative DC corona produces discrete active spots called 'tufts' along the corona wire, while the positive DC corona induces a uniform glow around the wire [17]. This also affects the behaviour of the discharges.

In another side, Beyond a certain voltage V_c (breakdown voltage), a disruptive discharge occurs, with the presence of sparks or possibly an electric arc [17].

This voltage is higher in the case of negative discharge. As a result, the V_c–V_s gap is greater for negative polarity.

For both negative and the positive polarities, the I-V curves of "all cylinders grounded" and "interior cylinders grounded" are quasi-identic, because of the small distance between the wire and the interior cylinders, which are grounded in these two cases. However, the onset voltage of the corona discharge in cases where only the outer cylinder is grounded is higher than that in the other two cases.

When the internal cylinders are not connected to the ground, it blocks the way of charge carriers towards the exterior cylinder. As a consequence, the internal cylinders acquire an electric floating potential, and generate a novel electric field lines between the two types of cylinders. The difference of potential between the wire and the interior cylinders in this case is low which decreases the electric field magnitude compared to the cases where all the cylinders are grounded.

Fig. 4 shows the current-voltage characteristics of the ESP for negative polarity with the presence of particles.

The presence of incense particles modifies the dynamics of the current–voltage curves. Indeed, for the same applied voltage, the current is lower with particles when the voltage is higher than the ionization threshold value. This could be mainly explained by the lower mobility of these submicron particles compared to ion mobility, but also due to the complex process of charge transfer between ions and particles [18, 19].

The evolution of the average power consumption as function of applied voltage for the three cases of grounding electrodes is shown in Fig. 5. The power consumption is obviously lower when only the exterior cylinder is grounded compared with the two other cases (where all the cylinders are grounded and the interior cylinders are grounded). Moreover, the maximum values obtained before the occurrence of the disruptive discharge (breakdown) did not exceed 1.5 W for the negative polarity.

Collection efficiencies

The collection efficiency η of the ESP is defined as follows:

$$\eta(\%) = \left[1 - \frac{N_{On}}{N_{Off}}\right].100\% \quad (3)$$

where: N_{On} and N_{Off} – the number of particles per cm^3 for all particle classes with and without corona discharge respectively [18].

Fig. 6 presents the evolution of the collection efficiency as a function of the applied voltage. For a given voltage, the collection efficiency in the cases of "all cylinders grounded" and Interior cylinders grounded" is clearly higher (it can reach 100 % at 9 kV) compared to the case of "grounding only the exterior cylinder".

Fig. 7 shows the collection efficiency evolution as function of the electric power consumption.

It is observed that high collection efficiency (up to 100%) can be reached with relatively low power consumption (about 1.5 W) in the cases of "all cylinders grounded" and "Interior cylinders grounded".

Moreover, for the same efficiency, and when the exterior cylinder is grounded, the corona discharge is clearly less power consuming, as a result of the low current in this case (about 5 μA at 15 kV).

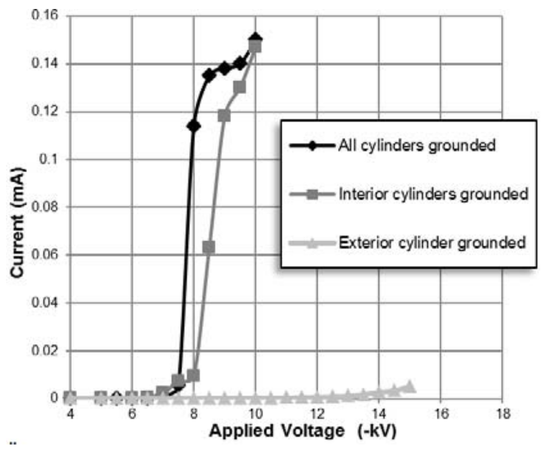

Fig.4. Current-voltage characteristics for negative corona discharges with the presence of particles.

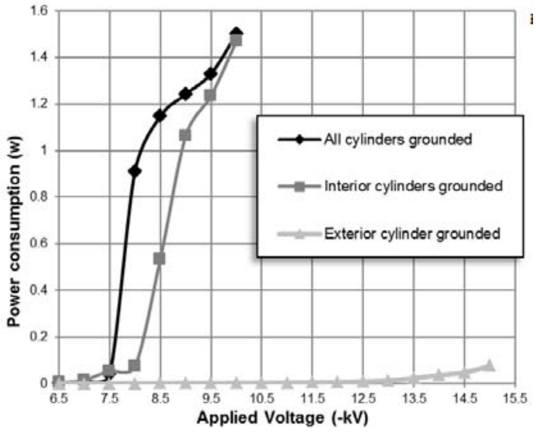

Fig.5. Power consumption versus voltage for negative corona discharges in the presence of particles.

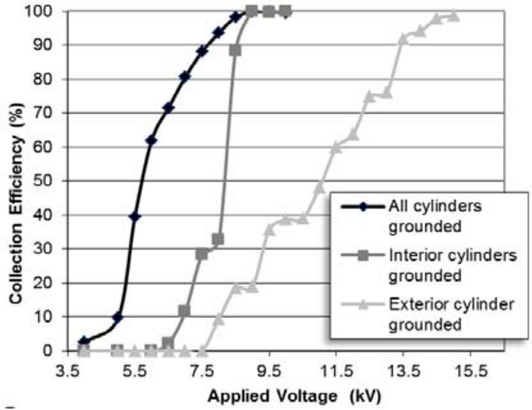

Fig.6. Particle collection efficiency as a function of the applied voltage.

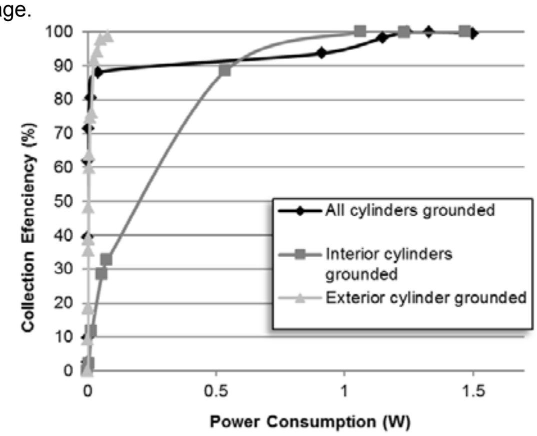

Fig.7. Particle collection efficiency as a function of power consumption for the three grounding cases.

Particle size and concentration

Fig. 8 shows the size distribution of the incenses particles without corona discharge and with corona discharge, for the three cases (a. all cylinders grounded; b. interior cylinders grounded; c. only the exterior cylinder grounded) when the applied voltage is fixed at 9 kV, in the indicated conditions.

Zukeran et al. [20] have shown that the size distribution of solid particles of incense smoke after drying reached a maximum between 0.2 and 0.3 µm diameter, which is in good agreement with the result indicated in Fig. 8.

The results show that when a high voltage is applied (above 4 kV when the interior cylinders and all cylinders are grounded, and 7 kV when the exterior cylinder is grounded), a corona discharge is generated around the active electrode, and then the concentration of particle decreases for all sizes in the three cases.

When all cylinders were grounded, the spectrometer counted only one particle at the outlet of the ESP. This indicates that almost all of inlet particles are electrically charged and collected on the grounded electrodes.

In the other side, when the interior cylinders were grounded, 99.9% of particles are collected at 9kV; and 100% of them are collected at 9.5 kV which means that the spectrometer counted no particle at the outlet of the ESP.

However, when only the exterior cylinder is grounded, for diameter range greater than 0.5 µm, the concentration of particle is almost zero.

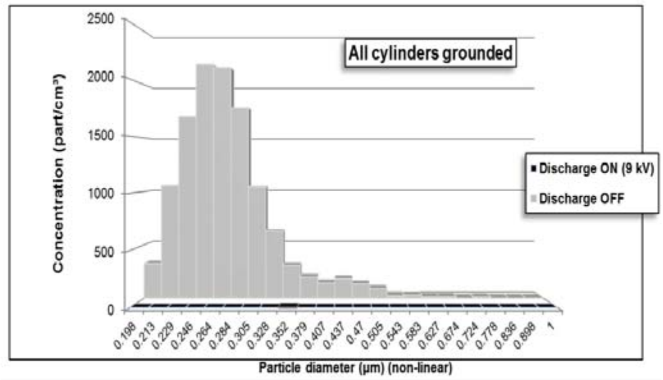

Fig.8.a. Granulometric Distribution of incense particles when All the cylinders are grounded

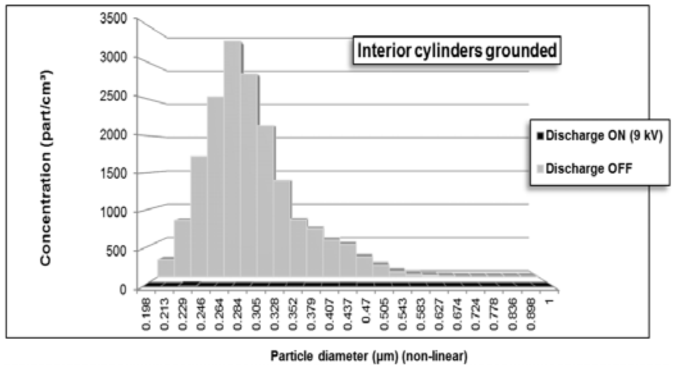

Fig.8.b. Granulometric Distribution of incense particles when the Interior cylinders are grounded

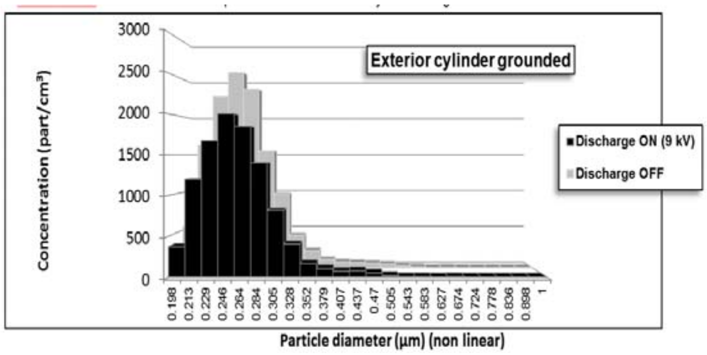

Fig.8.c. Granulometric Distribution of incense particles when the Exterior cylinder is grounded

Conclusions

In the present work, a novel ESP configuration has been tested experimentally to improve the wire to multi-cylinders geometry concept. The following conclusions can be drawn on the basis of data obtained:

1. In accordance with expectations, the electrical measurements show that corona discharge behaviour is similar to that obtained in wire-to-cylinder configuration. In fact, the negative DC corona produces a higher current compared with the positive DC corona.

2. The maximum efficiency is achieved when all cylinders were grounded; this arrangement provides an intense electric field distribution and an additional particle collection section.

3. Reducing the energy consumption is possible using the studied ESP. Results show that high collection efficiency (up to 100%) can be reached when all cylinders are grounded with relatively low power consumption (1.5 W). In addition, for the same efficiency, the negative applied voltage value was less than 9 kV.

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