Charge-Decay Characteristics of Granular Materials Forming Monolayers at the Surface of Grounded Electrodes

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***Abstract*—Laboratory studies and in-field observations have shown that the charge-decay characteristics of the granular materials at the surface of the grounded roll electrode significantly influence the outcome of the electrostatic separation process. This paper validates an indirect method of charge-decay characterization, based on the measurement of the electrical potential at the surface of a monolayer of granular insulating material. The study was performed on three materials—polyvinyl chloride, polyethylene, and rubber—extracted from chopped electric wire wastes. The granules (characteristic size in the range 1–4 mm) were disposed on the surface of a grounded plate electrode (layer area: 100 mm × 100 mm; electrode area: 200 mm × 200 mm). A wire-type corona electrode, energized from a dc high-voltage supply, was employed for charging the granules. The potential due to the charge at the surface of the granular layer was measured with the capacitive probe of an electrostatic voltmeter connected to a personal computer. Data acquisition and processing were done using the LabView environment. The influence of particles characteristics and of ambient factors was studied. The findings enabled a more accurate modeling of discharging phenomena that affect the performances of electrostatic separators. The method can be easily adopted in electrostatic discharge studies for material characterization.**

***Index Terms*—Charging and discharging, fundamentals, measuring techniques.**

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I. INTRODUCTION

THE CORONA effect is widely employed for charging the granular mixtures processed in roll-type electrostatic separators [1]. Therefore, a lot of work has been done to characterize the wire-, needle-, or blade-type corona electrodes employed in these installations [2], [3], and to compute the electric field strength E, as well as the ionic charge density q they generate [4], [5]. Experimental techniques have also been developed for estimating the corona charging conditions of insulating particles that form a layer at the surface of a grounded electrode [6]. Lately, experimental design methodology has been employed for evaluating the effects of various factors (electrode position, roll speed, ambient conditions) on the efficiency of particle charging and separation [7], [8]. Physical models of the corona charging process and of the separation trajectories have been elaborated, but they fail to explain the observations made under certain environmental conditions [9].

One such observation is that the mass of the collected insulating particles diminishes when the roll speed decreases, if the relative humidity of the ambient air exceeds 60% [8]. This phenomenon is supposed to be related to the fact that the charge of the particles in contact with the grounded rotating roll electrode decreases faster if the ambient humidity affects their superficial and global conductivity. In order to validate this hypothesis, attempts have been made to develop appropriate experimental techniques for characterizing the behavior of various granular materials in conditions that simulate those encountered in industrial roll-type electrostatic separators. The method presented in a previous paper [10] and based on the use of a Faraday pail gives good results for large particles (characteristic size: 5 mm), but is not effective for smaller ones (<2 mm).

The aim of this paper is to validate an indirect method to characterize the discharge of insulating particles in contact with a grounded electrode. The basic idea consists in measuring the decay with time of the potential V in a point at the surface of a monolayer of granular material, by means of an electrostatic voltmeter [11], using a sensing probe close to that surface, but without contacting it [12]. The capacity C of the probe–layer system being constant, the potential V is proportional to the local surface charge density q of insulating granular material, and its decay reflects that of q.

II. THEORETICAL ASPECTS

The electric field of the most widely used industrial electrostatic separators is generated between a corona electrode, which

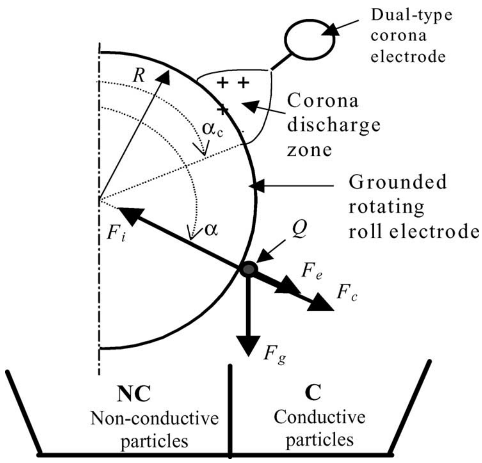

Fig. 1. Forces acting on a charged insulating particle at the surface of a rotating roll electrode connected to the ground.

can be of a dual type, as in Fig. 1, connected to a dc high-voltage supply, and a grounded rotating roll electrode. The intensity E of the electric field at the surface of the roll electrode is a function of the angular position α: $E = E(\alpha)$. The particles to be separated are fed onto the surface of the roll electrode at an angle $\alpha = 0°$. While rotating at an angular speed ω, the roll electrode carries them through a well-defined corona discharge zone. Subjected to "ion bombardment," a spherical insulating particle of radius a acquires a charge Q, which is a function of the time t spent in the corona discharge, zone, and of the electric field E [9], [10]. The charged particle is then subjected to two electric forces.

1) The electric field force:

$$F_e = QE. \tag{1}$$

2) The electric image force:

$$F_i = \frac{Q^2}{4\pi\varepsilon_0 a^2}. \tag{2}$$

The insulating particles of mass m are expected to detach from the surface of the electrode of radius R, rotating at an angular speed ω, at an angle α_d when

$$F_c + F_{gn} > F_e + F_i \tag{3}$$

where F_c is the centrifugal force

$$F_c = m\omega^2 R \tag{4}$$

and F_{gn} is the normal component of the gravitational force

$$F_{gn} = -mg \cos \alpha. \tag{5}$$

If the particles are assumed to attain instantaneously and preserve indefinitely the saturation charge $Q = Q_s$ given by Pauthenier's formula [9], [10], the electric image force is constant. With $E \approx 0$ for $90° < \alpha$, the electric force F_e can be neglected and (3) becomes

$$F_c + F_{gn} > F_i. \tag{6}$$

As $F_c + F_{gn}$ is maximum for $\alpha = 180°$, the detachment should occur at an angle $90° < \alpha_d < 180°$ or not at all. If $\omega_1 > \omega_2$, the centrifugal force increases and the particles should detach sooner from the roll electrode: $\alpha_{d1} < \alpha_{d2}$. The electrostatic separation experiments contradict these predictions: many insulating particles detach at $\alpha_d > 180°$. When the separation tests are carried out in a relatively humid air (RH > 60%), the particles detach easier at lower speeds ($\alpha_{d1} > \alpha_{d2}$, if $\omega_1 > \omega_2$).

This can be explained by the fact that even if the particles are charged at saturation in the corona discharge zone, their charge Q is not constant, but a function of time $Q(t)$. In contact with the roll electrode, the particles progressively loose their charge. With F_i and F_e decreasing with time, some particles that would otherwise remained pinned to the surface of the roll electrode will detach at $180° < \alpha_d < 270°$. On the other hand, the charge decay will be faster for humid particles, which are characterized by higher (superficial) conductivities. With the roll electrode rotating at low speed, the decrease of the electric charge Q carried by the particle can be significant. It is, thus, possible that the sum of the electric forces $F_i + F_e$, which is proportional to Q, becomes less than the centrifugal force F_c. As a consequence, the particles will detach easier from the surface of the roll electrode, in spite of the diminution of F_c at low ω.

The detachment angle is a solution of the implicit equation:

$$Q(t(\alpha))E(\alpha) + Q(t(\alpha))^2/(4\pi\varepsilon_0 a^2) = -mg \cos \alpha + m\omega^2 R \tag{7}$$

with

$$t(\alpha) = \frac{\alpha - \alpha_c}{\omega} \tag{8}$$

where α_c designates the limit of the corona discharge at the surface of the roll electrode, i.e., the starting point of the discharge process.

The experiments described in the next sections of the paper were designed to find the expression of $Q(t)$ for various materials and under various operating conditions, in an attempt to improve the physical model of insulating particle behavior in roll-type separators.

III. Materials and Method

The experiments were carried out on three materials, polyvinyl chloride (PVC), polyethylene (PE), and rubber, which are usually found in the nonconductive granular mixtures processed in roll-type electrostatic separators. They had been extracted in aqueous solution from a genuine sample of chopped electric wire wastes (RIPS-ALCATEL, France). The sorted materials were dried in compressed air flow (10 °C for 10 min), and then, kept in contact with the ambient air at 20 °C ± 0.5 °C and relative humidity 40% ± 2% for 12 h, before being subjected to the charge-decay characterization procedure described hereafter. Two samples of PVC were prepared: S1.1, with granule size ranging from 1 to 2 mm, and S1.2, composed of granules larger than 2 mm (maximum size: 4 mm). The PE sample

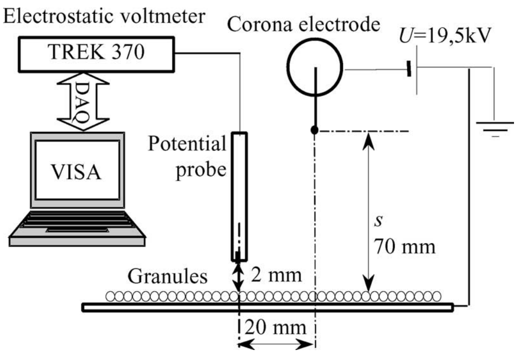

Fig. 2. Experimental setup for the study of corona charging and discharging of granular layers of insulating particles at the surface of a grounded electrode.

(S2) consisted of flakes of less than 2 mm in diameter, while the rubber sample (S3) contained isometric particles with the characteristic diameter in the 1–2 mm range.

In all the tests, the particles formed a compact monolayer at the surface of a grounded plate electrode (layer area: 100 mm × 100 mm; electrode area: 200 mm × 200 mm). They were subjected for 10 s to a negative dc corona discharge generated by a wire-type dual electrode [3], energized from a high-voltage supply (model SL100PN300, Spellman). The wire was parallel to a plate electrode, at a distance $s = 70$ mm (Fig. 2).

The electric potential due to the charge in a well-defined point at the surface of the granular layer was measured with the capacitive probe of an electrostatic voltmeter (model 370, TREK), driven by a personal computer through an IEEE488 interface. During the 2 s charging period, the probe was kept at a distance of 100 mm from the corona field. When the high-voltage power supply was switched OFF, a spring-actuated device moved the probe to the measuring position, 2 mm above the granules, and 20 mm away from the axial plane of the electrode system.

The potential decay was displayed on a virtual instrument developed in the LabView environment. The data were stored in .txt files that could be transferred for further processing in EXCEL. From the data recorded for each test, it was possible to evaluate the characteristic charge-decay time t_d, as the laps of time needed for the initial charge $Q(0) = Q_{\max}$ to reduce to half of the maximum value $Q_{\max}$, i.e., $Q(t_d) = Q_{\max}/2$.

Test #1 was performed with the samples S1.1 and S1.2 as obtained from the preparation procedure described before. Prior to test #2, the sample S1.2 was subjected to a thermal conditioning operation for 30 min in a 60 °C air flow. Test #3 involved the samples S2 and S3. All the tests were performed in ambient air, at 20 °C ± 0.5 °C and relative humidity 40% ± 2%.

IV. Results and Discussion

The potential decay curves displayed by the virtual instrument for samples S1.1 and S1.2 characterized in test #1 can be examined in Fig. 3. The initial time ($t = 0$ s) on these curves corresponds to the moment when the potential probe has arrived in the measuring position defined in Fig. 2. The time between the end of the charging and the beginning of the measurement was the same for all tests: ∼ 10 ms. Sample S1.2, composed of coarser particles, is characterized by a higher initial value of the surface potential (i.e., a higher initial charge acquired in the corona discharge) than is S1.1. A comparison between the time needed for the surface potential of each sample to reduce at half of its initial value ($t_d \approx 5.6$ s for S1.1 and $t_d \approx 3.1$ s for 1.2) shows that finer particles are likely to loose their charge faster than do coarser ones. This is probably due to the fact that the superficial conductivity is the main discharge mechanisms of the particles in contact with the electrode. The charge accumulated at the surface of coarser particles has a longer path to the ground than that on finer particles.

The curves are average of at least five measurements. In spite of the fact that the particles have slightly different shapes and sizes, the nonuniformity of the granular layer does not induce a great dispersion in the results: the standard deviation in each point of the charge-decay curves is of less than 3.5%. This is due to the principle of operation of the capacitive probe, which does not measure an individual charge, but integrates the potential information given by several particles that differ in shape and size.

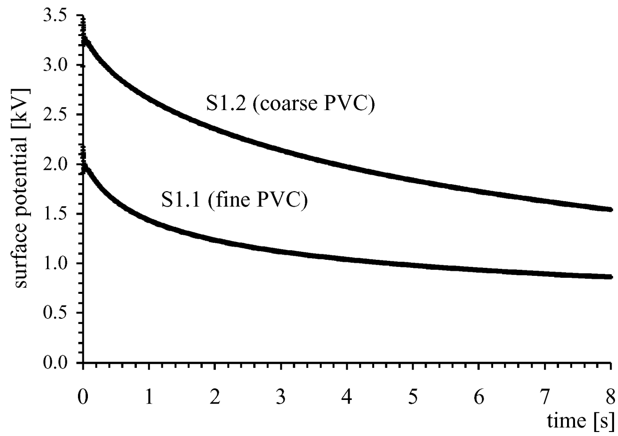

Fig. 3. Surface potential decay of fine (sample S1.1) and coarse (sample S1.2) PVC particles. Each curve is the average of at least five measurements (the standard deviation σ was less than 3.5% at any point).

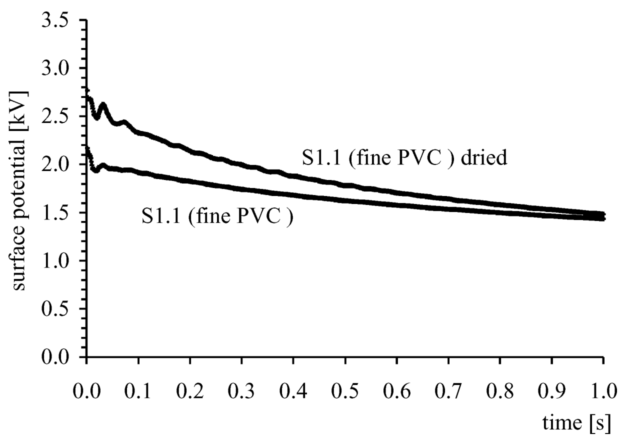

Fig. 4. Surface potential decay of fine PVC particles before and after drying for 30 min in hot airflow (60 °C). Each curve is the average of at least five measurements (the standard deviation σ was less than 3.5% at any point).

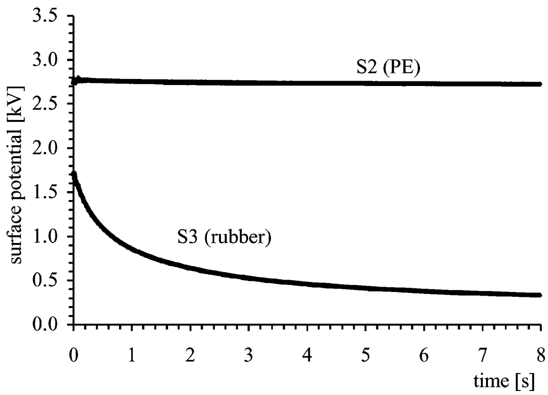

Fig. 5. Surface potential decay of PE (S2) and rubber (S3) particles. Each curve is the average of at least five measurements (the standard deviation σ was less than 3.5% at any point).

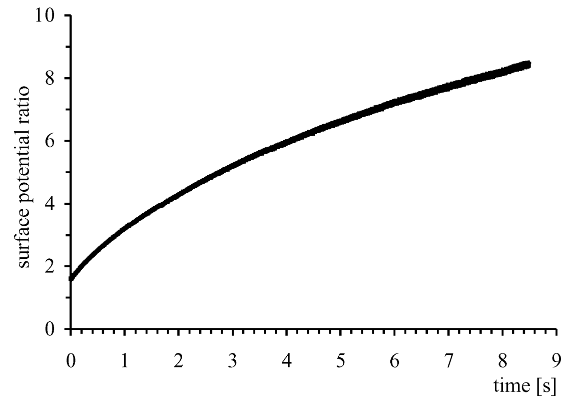

Fig. 6. Surface potential charge ratio of PE versus rubber particles.

Unsurprisingly, drying affects the discharging process to a significant extent, as shown by the curves in Fig. 4, obtained for sample 1.1. Similar results were recorded for sample 1.2. As the charging conditions were similar for the dried and undried samples, the fact that at $t = 0$ s, the former is characterized by a higher surface potential indicates that superficial moisture accelerates the discharge of the latter. After a certain time lapse, when the charge decay related to this physical mechanism is over, the surface potential variation of the dried and undried samples tend asymptotically to the same curve.

The potential decay is strongly dependent on the nature of the granular material. During 8 s, the surface potential of sample 2, composed of PE particles, a material that is known to be an excellent insulator, diminishes by less than 2%, from about 2.75 kV, to about 2.7 kV (Fig. 5). Under similar experimental conditions, the surface potential of the rubber particles in sample 3 diminishes from 1.7 to 0.85 kV, in less than 1 s. Rubber and PE particles are slightly different in shape and size, but this cannot explain the radically different behavior in contact with the grounded electrode. The charge carried by the rubber particles decay faster as their conductivity is higher that that of PE granules. In Fig. 6, the ratio of the surface potential of the two samples is given as a function of time. It can be concluded that after 9 s, a PE particle will carry a charge that is eight times that of a rubber particle of similar size. Also taking into account the shape difference between the two particles, the ratio between the electric image forces acting, respectively, on the PE and rubber particles is expected to be close to 10, which means that the two sorts of particles could be separated on a roll-type electrostatic separator.

In order to validate this assumption, a simple experiment has been carried out with a mixture of 50% PE and 50% rubber particles, using a laboratory roll-type corona separator. The grounded electrode of radius $R = 128$ mm was rotating at a very low speed (3 r/min), and the corona electrode was positioned so that $\alpha_c = 25°$. In spite of the fact that the time spent by the particles at the surface of the rotating grounded electrode was rather short (less than 0.5 s), the difference in the charge-decay characteristics of the two constituents of the granular mixture was enough to ensure the selective sorting of the constituents of the PE/rubber mixture (Table I). However, the coarser fraction of PE particles, representing 25% of the feed, were found in the conductive product, as the effect of the centrifugal force surpassed that of the image force. At the same time, 29% of the rubber was collected with the nonconductor fraction, which means that the time spent in contact with the grounded roll electrode was not long enough for some of the particles to loose enough of their charge for the electric image force to be surpassed by the centrifugal force. Using a belt-type electrostatic separator allowing particles to spend longer times in contact with the grounded electrode (i.e., the belt) would lead to much better separation results.

TABLE I
Results of an Electrostatic Separation Test Performed on a Granular Mixture of PE and Rubber

	PE [%]	Rubber [%]	Total [%]
Feed	50	50	100
NC Product	75	29	52
C Product	25	71	48

V. Conclusion

The experimental method presented in this paper makes possible a thorough description of a major physical phenomenon taking place in roll-type electrostatic separators: discharging of insulating particles in contact with the grounded electrode. With known charge-decay characteristics of the constituents of a granular mixture, numerical simulations can better predict the outcome of an electrostatic separation process.

In addition to facilitating such feasibility studies, the material characteristics obtained with this method can be used to develop new applications and to establish the initial conditions for experimental designs aiming at optimizing existing processes. Further developments of this method will lead to improved charge control techniques in various fields of applied electrostatics, including electrostatic discharge prevention.

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