# Controlling Particle Trajectory in Free-Fall Electrostatic Separators

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***Abstract*—The purity and recovery of concentrates obtained in industrial free-fall electrostatic separators can be increased by preventing the impacts between the particles and the electrodes. The aim of this paper is to analyze the possibility to control particle trajectories in such separators by modifying the conditions of particle admission in the interelectrode space. The parametric equations of a charged particle trajectory in the electric field between the electrodes of a free-fall separator served for writing a numerical modeling program in MATLAB. The ten control factors of the free-fall electrostatic separation process were employed as input variables of this program: particle charge and dimension, trajectory start point coordinates, feed input angle and initial velocity, electrode length and inclination, interelectrode spacing, and applied high voltage. A custom-designed laboratory free-fall electrostatic separator (length of the electrodes: 1000 mm; standard interelectrode spacing: 300 mm; and nominal high voltage: 90 kV), provided with a fluidized-bed tribocharger, was employed for validating the conclusions of the numerical modeling. The geometrical data of this separator were taken into account for computing the initial velocity $\nu_0$ of the particles entering the electric field zone. Another important parameter of the numerical model, which is the granule charge $q$, was attributed the value measured at the exit of the fluidized-bed tribocharger. The numerical simulations were performed for the two values of the feed input angle: $\alpha = 4^\circ$ and $\alpha = 8^\circ$, considering polyethylene therephtalate (PET) and polyvinyl chloride (PVC) particles of different sizes. A good agreement was found between the theoretical predictions and the results of the experiments carried out with two binary mixtures: 50% PET/50% PVC and 10% PET/90% PVC. Both the numerical modeling and the experimental study demonstrated that the feed input angle $\alpha$ influences the outcome of the electrostatic separation to a great extent.**

***Index Terms*—Electrostatic processes, numerical simulation, particle trajectory, triboelectrostatic separator.**

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## I. Introduction

An increasing number of applications, most of them in mineral processing [1]–[3] and recycling industries [4], [5], make use of free-fall electrostatic separators to take advantage of their relatively larger throughput capacity as compared with other types of installations (roll-type or plate-type electrostatic separators). The tribocharging device and the electrode system are essential elements characterizing the triboelectrostatic free-fall separator. Several technical solutions have been patented [6], [7] or described in the literature [8]–[11].

Industrial practice reveals the importance of the input feeder in obtaining high purity and recovery concentrates [12]. This can be easily explained by the fact that the trajectory of a charged particle in a free-fall electrostatic separator is influenced by the position in which the particle is introduced in electrostatic field and the initial particle velocity [13].

A delicate problem of the input feeder is the adjustment of the input angle $\alpha$ (Fig. 1). When $\alpha = 0$, the light particles with the same mass but different positive charges describe distinct trajectories [Fig. 1(a)]. The normal trajectory of a positively charged particle ends in the compartment of the collector situated under the negative electrode.

The higher positively charged particles hit the negative electrode and are deviated as impurities in the collecting compartment located under the positive electrode or are retained by the image force on the negative electrode surface. If the angle $\alpha$ is appropriately chosen [Fig. 1(b)], the collisions with the electrode can be avoided.

This paper presents the numerical simulation and the experimental study of charged-particle trajectories in a free-fall electrostatic separator for different feed input angles.

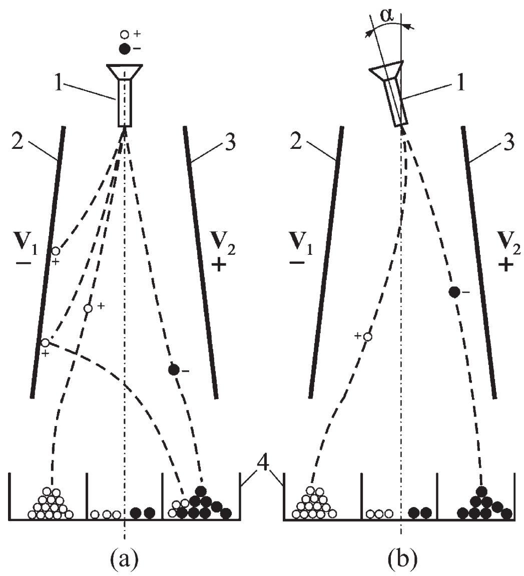


Fig. 1. Charged-granule trajectories in the electrostatic field of free-fall separator for (a) the vertical in-feed and (b) the inclined in-feed. 1) Adjustable angle input feeder. 2) and 3) Plate electrodes. 4) Collector. $\alpha$) Feed input angle.

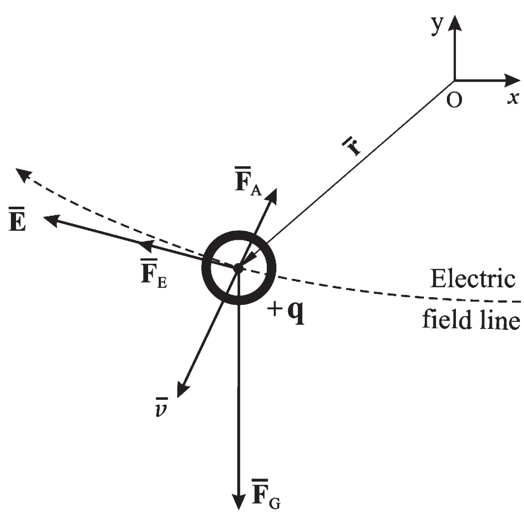


Fig. 2. Forces acting on a charged particle in a free-fall electrostatic separator.

## II. Mathematical Model of Particle Trajectories

The motion of a charged particle in the electrostatic field $\boldsymbol{E}$ of the free-fall separator (Fig. 2) takes place under the action of the gravitational force $\boldsymbol{F}_G$, electrical field force $\boldsymbol{F}_E$, and air frictional force (drag force) $\boldsymbol{F}_A$, according to the vectorial equation

$$m\frac{d^2F}{dt^2} = \overline{F_G} + \overline{F_E} + \overline{F_A} \tag{1}$$

where $m$ is the particle mass, and $\boldsymbol{r}$ is the position vector of particle mass center.

The magnitudes of the forces in (1) are given by the following:

$$F_G = mg \tag{2}$$
$$F_E = qE \tag{3}$$
$$F_A = \frac{1}{2}C_D\rho_A S\nu^2 \tag{4}$$

where $g$ is the gravity acceleration, $q$ is the particle charge, $E$ is the electric field strength, $C_D$ is the drag coefficient, $\rho_A$ is the air density, $S$ is the particle projected surface on motion direction, and $\nu$ is the particle velocity.

The electrostatic field of free-fall separator has plan-parallel symmetry. Particle trajectory, described by the position vector $\boldsymbol{r}(x, y)$, represents a plane curve which may be approximated by linear segments. On each trajectory segment, corresponding to a time increment $\Delta t$, the motion is considered rectilinear and uniformly accelerated (acceleration is constant), and the velocity increases with a quantity $\boldsymbol{a}.\Delta t$.

Thus, for the segment $[i, i+1]$, where the initial vectorial quantities $\boldsymbol{r}_i(x_i, y_i)$, $\boldsymbol{v}_i(v_{ix}, v_{iy})$, and $\boldsymbol{a}_i(a_{ix}, a_{iy})$ are known, the position vector of the point $(i+1)$ is given by the vectorial equation

$$\overline{r}_{(i+1)} = \overline{r}_i + \overline{\nu}_i\Delta t + \frac{1}{2}\overline{a}_i\Delta t^2. \tag{5}$$

To determine the next point of trajectory $\boldsymbol{r}_{(i+2)}$, it is necessary to calculate the velocity $\boldsymbol{\nu}_{(i+1)}$ and acceleration $\boldsymbol{a}_{(i+1)}$ in the point $(i+1)$

$$\overline{\nu}_{(i+1)} = \overline{\nu}_i + \overline{a}_i\Delta t \tag{6}$$
$$\overline{a}_{i+1} = \frac{1}{m}\left[\overline{F}_G + \overline{F}_{E(i+1)} + \overline{F}_{A(i+1)}\right]. \tag{7}$$

The trajectory parametric equations in Cartesian form, corresponding to the vectorial equations (5)–(7), are as follows:

$$\begin{cases} x_{(i+1)} = x_i + \nu_{ix}\Delta t + \frac{1}{2}a_{ix}\Delta t^2 & (8)\\ y_{(i+1)} = y_i + \nu_{iy}\Delta t + \frac{1}{2}a_{iy}\Delta t^2 & (9)\end{cases}$$

$$\begin{cases} \nu_{(i+1)x} = \nu_{ix} + a_{ix}\Delta t & (10)\\ \nu_{(i+1)y} = \nu_{iy} + a_{iy}\Delta t & (11)\end{cases}$$

$$\begin{cases} a_{(i+1)x} = \frac{1}{m}\left[-qE_{(i+1)x} + F_{A(i+1)x}\right] & (12)\\ a_{(i+1)y} = \frac{1}{m}\left[-mg + qE_{(i+1)y} + F_{A(i+1)y}\right] & (13)\end{cases}$$

where

$$\begin{cases} F_{A(i+1)x} = \frac{1}{2}C_D\rho_A\nu^2_{(i+1)x}\text{sign}\left[\nu_{(i+1)x}\right] & (14)\\ F_{A(i+1)y} = \frac{1}{2}C_D\rho_A\nu^2_{(i+1)y}\text{sign}\left[\nu_{(i+1)y}\right]. & (15)\end{cases}$$

In the start point of the trajectory $(i = 0)$, the initial quantities are as follows:

$$\begin{cases} \overline{r}_0(x_0, y_0 = 0)\\ \overline{\nu}_0(\nu_{0x} = \nu_0\sin\alpha, \nu_{0y} = -\nu_0\cos\alpha)\\ \overline{a}_0(a_{0x} = 0, a_{0y} = -g). \end{cases} \tag{16}$$

Particle trajectory, as can be observed in (12), (13), and (16), depends on the electric field strength $(E_x, E_y)$, the particle charge $q$, the particle mass $m$, the input position $(x_0, y_0)$, the initial velocity $\nu_0$, and the input angle $\alpha$.

The parametric equations of trajectory (8) and (9) are differential equations of second order that can be integrated by an approximation method using MATLAB 7.0. The original program, written by authors, simulates the 2-D trajectory of a particle in free-fall separator.

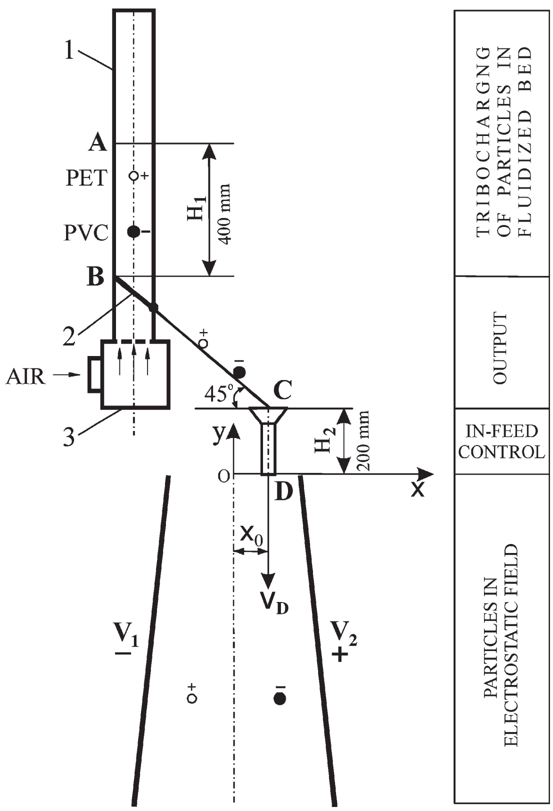


Fig. 3. Schematic representation of the free-fall triboelectrostatic separator.

The Cartesian components of electric field strength, in each point of trajectory, were determined by approximating the field lines by circular arcs. The time increment $\Delta t$ was chosen 1 ms.

The input data for trajectory simulation are the following: the length of the plate electrodes, the vertical inclinations of the electrodes, the interelectrode gap, the initial point coordinates of trajectory, the particle initial velocity, the feed input angle, the particle charge, the particle diameter, the mass density of the particle, the potential difference between electrodes, the drag coefficient, and the air density.

Particle initial velocity $\nu_0$ and particle charge $q$ are application specific quantities, which are evaluated and measured further, as shown in the next section of this paper.

## III. Materials and Method

### A. Granules Characterization

The materials used for trajectory study in free-fall separator (Table I) are millimeter-size virgin granules of polyethylene therephtalate (PET) and polyvinyl chloride (PVC). By using PET and PVC granules of different colors, it was easier to analyze the purity and the extraction of the concentrates in the electrostatic separation tests.

The average mass of the granules was experimentally determined by weighting 1000 particles.

### B. Experimental Setup

The tribocharging process of the PET/PVC mixture was carried out in a fluidized-bed device [14]. Charging is mainly produced by multiple collisions between PET and PVC particles. However, the charge of the particles is amplified in contact with polypropylene (PP) walls of the tribocharging chamber, as PVC is located on the left side and PET on the right side of PP in triboelectric series [15] (Table I). By opening the output door of the fluidized-bed device, the charged particles leave the tribocharging chamber by free-fall motion, slide freely along an inclined plane at 45°, enter in the adjustable input feeder, and are introduced in the electrostatic field of the free-fall separator (Fig. 3).

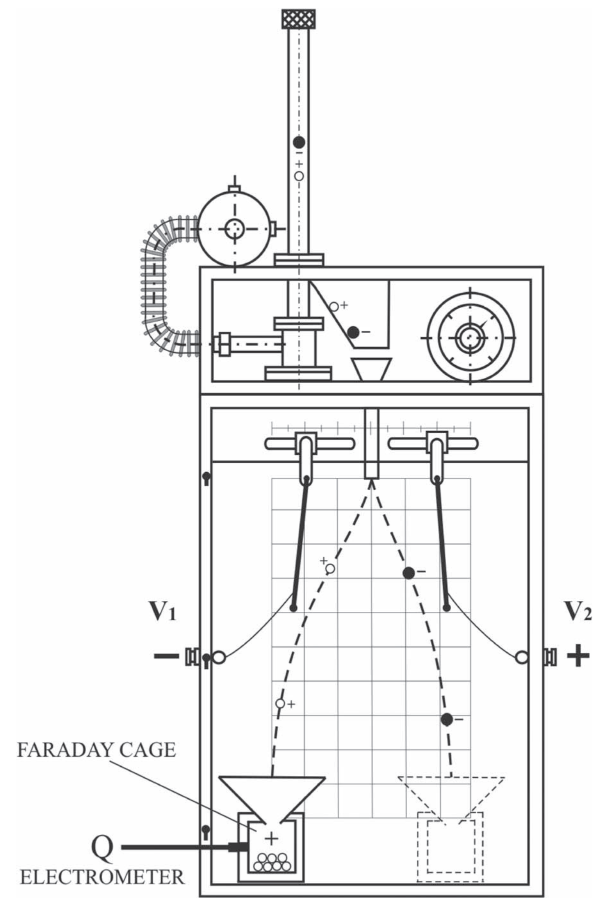


Fig. 4. Experimental setup for evaluating the electrical charge of the granules.

In a first group of experiments, aimed at estimating the charge/mass ration, the standard 1000-mm plate electrodes, vertically inclined at 5° and spaced at 300 mm, were replaced by shorter ones (400 mm in length), so that a Faraday cage, connected to a digital electrometer, could be placed under the electrodes in the collecting zone (Fig. 4). Eight samples, consisting of 25 g of PET and 25 g of PVC, were prepared for these measurements. To determine the PET particle charge, the Faraday cage was located under the negative electrode. Each 50-g sample was tribocharged for 60 s in the fluidized-bed device, using the air generated by a turbo blower at 38 °C and 20% relative humidity. Charged granular mixture was introduced in the electrostatic field of separator by means of the input feeder, adjusted to $\alpha = 0$. Under the action of the separation forces, the PET particles were deviated toward the negative electrode. In the Faraday cage, PET particles were collected only. The charge $Q$ indicated by the electrometer was

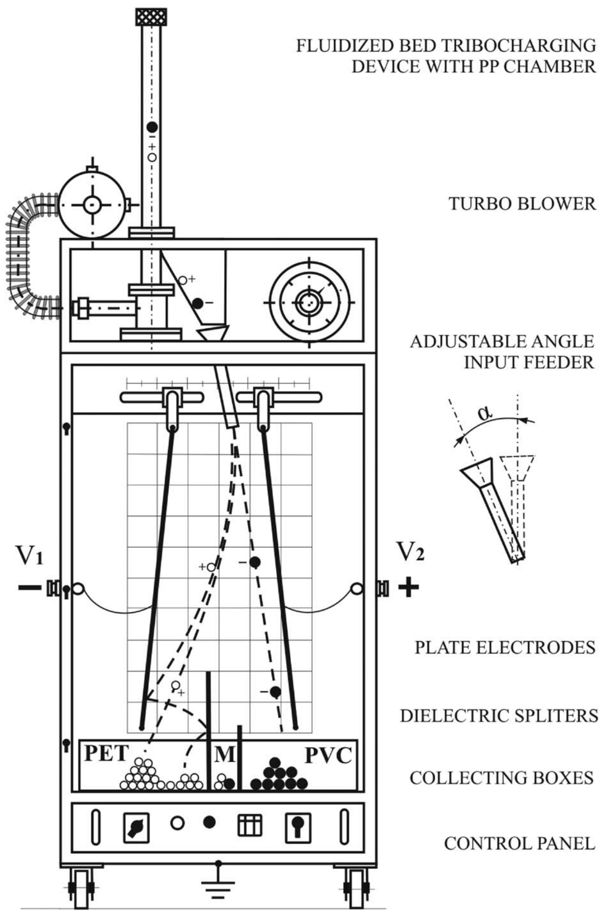


Fig. 5. Free-fall electrostatic separator equipped for the experiments of particle trajectory control by adjusting the input angle $\alpha$.

divided to the mass $m$ measured by an electronic balance and to the number $N$ of PET particles in a gram to determine the charge $q$ of a PET particle

$$q = (Q/m)/N. \tag{17}$$

This procedure was repeated four times to find out the minimum, maximum, and average charges of PET particle.

To evaluate the PVC particle charge, the Faraday cage was located under the positive electrode. Another set of four experiments was performed using the same procedure consisting in tribocharging, electrostatic separation, and charge measurement.

The second set and third sets of experiments were done with the standard electrode configuration of the laboratory free-fall electrostatic separator (Fig. 5). Their aim was to evaluate the efficiency of the electrostatic separation at various values of the feed input angle ($\alpha = 0^\circ, 4^\circ$, and $8^\circ$). A 400-mm-length dielectric splitter was located 30 mm on the left side of separator symmetry axis in order to prevent that the PET particles that hit the negative electrode are deviated in the middling (M) or the PVC concentrate. A second 200-mm splitter prevents the jumps of particles between M and PVC compartments. The other conditions were similar to those described for the first set of experiments. Samples containing 50% PET and 50% PVC were employed in the second set of experiments, whereas the third one was done with 10% PET/90% PVC granular mixtures.

TABLE I
PHYSICAL CHARACTERISTICS OF PLASTIC GRANULES

| Material | PET | PVC |
|---|---|---|
| Colour | White | Yellow |
| Size [mm] | 2.5x2x2 | Ø4.5x1.4 |
| Mass [mg] | 13.3 | 30.5 |
| Mass density [kg/m$^3$] | 1330 | 1370 |
| Triboelectric series | − PVC — PP — PET + | |
| Equivalent diameter [mm] | 2.86 | 4.06 |
| Number of granules per gram | 75 | 33 |

TABLE II
CHARGE ON PET AND PVC GRANULES ($\alpha = 0$; 50% PET/50% PVC)

| | | | | | | |
|---|---|---|---|---|---|---|
| PET (Plus) | Q/m [nC/g] | 16.32 | 19.82 | 16.08 | 18.26 | Avr |
| | q [nC] | 0.217 | 0.264 Max | 0.214 Min | 0.243 | 0.235 |
| PVC (Minus) | Q/m [nC/g] | 15.03 | 16.18 | 16.22 | 16.09 | Avr |
| | q [nC] | 0.458 Min | 0.493 | 0.495 Max | 0.491 | 0.484 |

## IV. EXPERIMENTAL RESULTS

### *A. Charge Measurements*

The results of the tribocharging process of the 50% PET/50% PVC mixture are given in Table II.

### *B. Electrostatic Separation Experiments*

Table III contains the results of the set of experiments carried out with the 50% PCV/50% PET samples. The purities and recoveries of both concentrates were better when $\alpha$ increased due to the diminishing number of elastic collision of PET particles with the negative electrode and to the barrier effect of the 400-mm splitter. This set of experiments pointed out the displacement of trajectories toward the positive electrode when the angle $\alpha$ increased, an effect that will be observed also in numerical simulation. The best results were obtained for $\alpha = 8^\circ$.

The results of the last group of experiments, shown in Table IV, revealed an increase of purity and recovery for both concentrates obtained from the 10% PET/90% PVC, when the input angle $\alpha$ varies from 0° to 8°.

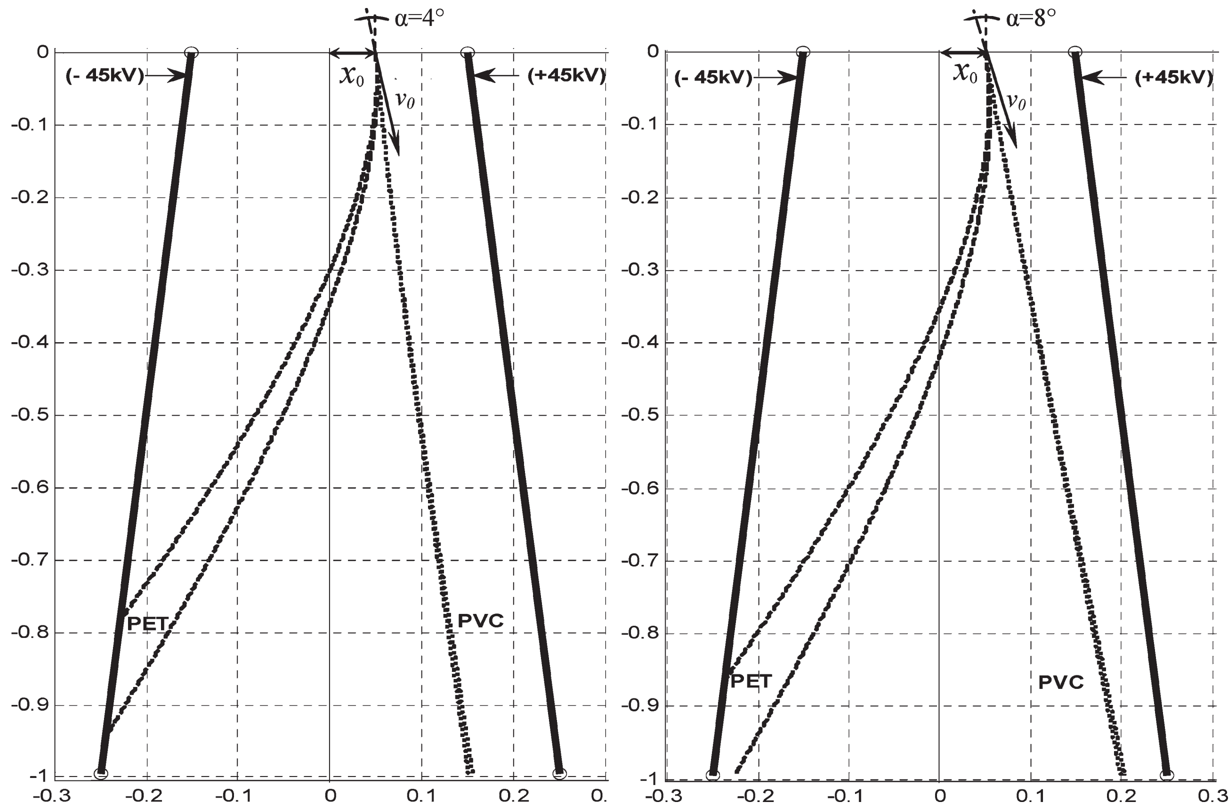


Fig. 6. MATLAB-plotted trajectories of PET and PVC particles for minimum and maximum charges and two input angles. The trajectories corresponding to the maximum charges are more deviated toward the electrodes due to stronger electrical forces.

TABLE III
RESULTS OF THE ELECTROSTATIC SEPARATION EXPERIMENTS CARRIED OUT WITH THE 50% PET/50% PVC SAMPLES (AVERAGE OF FIVE EXPERIMENTAL RUNS EACH)

| Products | α = 0° | | α = 4° | | α = 8° | |
|---|---|---|---|---|---|---|
| | PET | PVC | PET | PVC | PET | PVC |
| Purity | 98.8 | 93.3 | 98.8 | 93.7 | 99.6 | 96.1 |
| Recovery | 61.8 | 69.4 | 69.3 | 74.3 | 70.0 | 81.6 |

TABLE IV
RESULTS OF THE ELECTROSTATIC SEPARATION EXPERIMENTS CARRIED OUT WITH THE 10% PET/90% PVC SAMPLES (AVERAGE OF FIVE EXPERIMENTAL RUNS EACH)

| Products | α = 0° | | α = 4° | | α = 8° | |
|---|---|---|---|---|---|---|
| | PET | PVC | PET | PVC | PET | PVC |
| Purity | 98.8 | 93.3 | 98.8 | 93.7 | 99.6 | 96.1 |
| Recovery | 61.8 | 69.4 | 69.3 | 74.3 | 70.0 | 81.6 |

## V. NUMERICAL SIMULATION OF PARTICLE TRAJECTORIES

The initial velocity $\nu_0$ was calculated under certain assumptions (Fig. 3).

1) When the compressed air that supplies the fluidized-bed tribocharging device is turned off, the particles begin to fall freely in the tribocharging chamber from the average height $H_1$ with an initial velocity $\nu_A = 0$.
2) During particle movement on the inclined plane at the output of the tribocharging chamber, the velocity remains constant, as the tangential component of gravitational force is balanced by frictional force.
3) Adjustable input feeder is vertically positioned $(\alpha = 0)$, and its output velocity is the initial velocity of the particles falling freely in the electric field of the separator $(\nu_0 \approx \nu_D)$.

The computation was performed by taking into account the conversion of the initial potential energy of the particle in point $A$ into kinetic energy. Thus,

$$\nu_B = \sqrt{2gH_1} \tag{18}$$

$$\nu_C = \nu_B \cos^2 45^\circ = \frac{1}{2}\nu_B \tag{19}$$

$$\nu_0 \approx \nu_D = \sqrt{g(2H_2 + H_1/2)} = 2.4 \text{ m/s}. \tag{20}$$

The value given by (20) was introduced in the program that computed the particle trajectories for an electrode configuration similar to the one considered for the experiments presented in Section IV-B.

1) Electrode length is 1 m.
2) Interelectrode spacing is 0.3 m.
3) Vertical inclination of the electrodes is 5°.
4) Potentials of the electrodes are $V_1 = -45$ kV and $V_2 = +45$ kV.

The PET and PVC particles were approximated with equivalent spheres; the mass and equivalent diameter of which are given in Table I. The minimum and maximum charges of a type of particles were chosen as the extreme values in the series of four tests (Table II). The other input data were the drag coefficient ($C_D = 0.4$), the air density ($\rho_A = 1.22$ kg/m$^3$), the coordinates of the starting point ($x_0 = 0.05$ m; $y_0 = 0$), and the initial velocity ($\nu_0 = 2.4$ m/s).

The results of the numerical simulations can be examined in Fig. 6. The most affected by the electrostatic field were the trajectories of the PET particles carrying the maximum charge because of the higher ratio between the electrical and gravitational forces $F_{E\max}/F_G$. An increase of input angle from $\alpha = 4^\circ$ to $\alpha = 8^\circ$ rotates the assembly of the trajectories toward the positive electrode, so that the trajectory of the PET particle with minimum charge has no contact with the negative electrode.

## VI. Conclusion

The efficiency of free-fall triboelectrostatic separators depends not only on the charge acquired by the particles in the tribocharging device and the strength of the electrostatic field between the electrodes but also on the position and the configuration of the input feeder. The ideal separation of a binary mixture implies control of these three groups of factors for obtaining two distinct sets of particle trajectories.

An original simulating program of the particle trajectory in free-fall triboelectrostatic separator enabled the plot of particle trajectories by taking into consideration more than ten control variables. Numerical simulation and the experimental study of separation trajectories for two types of particles tribocharged in a fluidized-bed device pointed out the importance of field input angle $\alpha$ to improve the separation efficiency.

Both the experimental data and the computed results prove that the adjustment of the feed input angle may contribute significantly to a successful separation of a binary mixture of granular materials characterized by different particle masses or/and mixture ratios.

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Dr. Iuga is a member of the Electrostatics Society of America and a cofounder of the Electrostatics Society of Romania.