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Study of charged particles trajectories in free-fall electrostatic separators

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A B S T R A C T

The objective of this paper is to develop a mathematical model for computing the millimeter-sized particles trajectories in the free-fall electrostatic separator. The simulation involves the numerical solution of motion equations of the particles subjected to electric and gravitational forces. The air-drag force and the impact of the particles with the electrodes were also considered. The resolution algorithm is implemented as a MATLAB program that uses the results of electric field computation performed with COMSOL software. The model obtained is used to study the factors influencing the quality of the products recovered at the outlet of the separator.

1. Introduction

The free-fall electrostatic separators are widely used in sorting and purification of sub-millimeter size ores [1–4]. Currently, they are also successfully applied to the sorting of granular plastics from waste electrical and electronic equipment [5–8]. In these facilities, granular material sorting is produced by the electrostatic force acting on particles pre-charged in devices that use the triboelectric effect. The quality of products recovered at the outlet of the electrostatic separator is strongly related to the charge/mass (Q/m) ratios of the particles in the mixture [9,10].

Several triboelectric charging devices have been developed in recent years [10–13]. Currently, the fluidized bed is considered to be the best solution [14,15], as characterized by moderate energy consumption, as well as low operating and maintenance costs. Improving the tribocharging conditions by reducing the size of the treated particles is a way to increase the efficiency of the electrostatic separations.

However, particle size reduction is sometimes unnecessary and leads to an increase of the energy consumed for milling. Therefore, attempts were made to optimize the electrostatic separation of mm-size particles, by using numerical modelling techniques. Thus, Calin et al. [16] were the first to perform numerical modelling of particle trajectories in a free-fall electrostatic separator. However, the analytical method they employed for the electric field computation was far from being accurate, especially in the proximity of electrode edges. Recently, Younes et al. [17] compared the outcome of free-fall electrostatic separation experiments with the results of numerical simulations of particle trajectories, but the computational conditions were not very clearly described.

This paper aims at validating an accurate numerical model of particle trajectory in a free-fall electrostatic separator. The model uses information on the geometrical and electrical parameters of the separation system and of the physical characteristics of the particles of the product under study. Thus, it relies on measures of Q/m ratio performed for the constituents of a mixture (ABS/PVC) recovered at the outlet of a laboratory separator (Fig. 1).

The results obtained may be used to define the optimal values of the control variables of the separator that would give maximum gap between the collection points of two products, having different mass and charge distributions.

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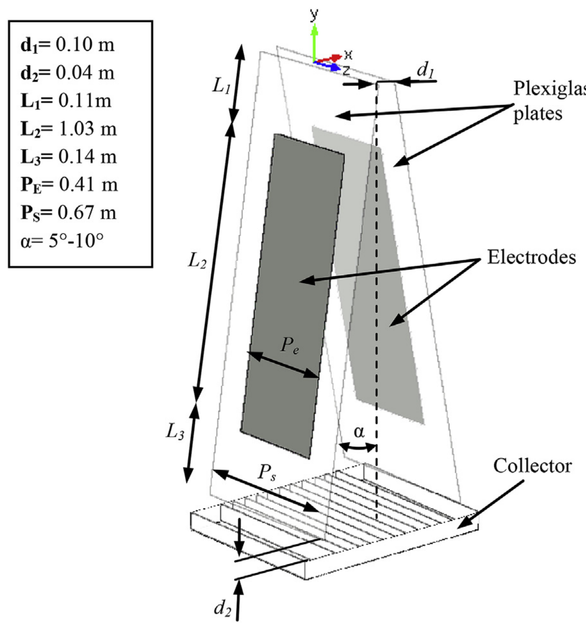

Fig. 1. Dimensions used in the free-fall laboratory separator.

2. Numerical simulation

The separator used in this study consists in two PMMA plates suspended in a rectangular tower of same material (Fig. 1). Each plate carries an aluminum electrode connected to a DC high-voltage supply, to generate the electric field zone in which the separation takes place. The inclination of the plates with respect to the vertical plane is adjustable.

The charged particles are introduced into the electric field zone through a funnel. The movement of the particles in this zone can be characterized by the equation:

$$m\frac{d\vec{v}}{dt} = \sum \vec{F} \tag{1}$$

where m and $\vec{v}$ represent respectively the mass and velocity of the particle and $\sum \vec{F}$ is the sum of the forces acting on the moving particle.

At every moment, the charged particles are subjected to an electrostatic force due to the action of the electric field in the inter-electrode zone. The distribution of the electric potential U in this area is given by the Laplace equation:

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} = 0 \tag{2}$$

The intensity E of the electrostatic field in the separation zone can then be calculated from:

$$E = -\nabla U \tag{3}$$

In this study, the solution of (2) is obtained using software specialized in solving partial differential equations by the finite element method (COMSOL). The results of calculations made by this method are shown in Fig. 2.

During their movements in the electrostatic separation zone, the charged particles are subjected to the force of gravity, electrostatic force and the friction force with the air.

The gravity force applied to a particle of mass m is:

$$\vec{F}_g = \begin{bmatrix} 0 \\ mg \end{bmatrix} \tag{4}$$

where m represents the mass of the particle and g = - 9.81 (m/s^2) is the gravitational acceleration.

The electrostatic force applied to a charged particle in the inter-electrode region can be assessed by:

$$\vec{F}_{el} = Q\vec{E} = Q\begin{bmatrix} E_x(x,y) \\ E_y(x,y) \end{bmatrix} \tag{5}$$

where Q is the electrical charge of the particle and E_x (x, y); E_y (x, y) components of the electric field vector.

The frictional force with the air applied to a particle is:

$$\vec{F}_a = \left(C_f \frac{1}{2}\rho\pi r_p^2 v\right)\begin{bmatrix} v_x \\ v_y \end{bmatrix} \tag{6}$$

where v_x and v_y are the x and y component of particle velocity $\vec{v}$; r_p: radius of the spherical particle of equal volume to the actual particle, C_f:friction coefficient between the particle and the air; ρ: mass density of the particle.

Substituting (4–6) into (1) gives the equation of motion:

$$ma_x(x,y) = QE_x(x,y) - \left(C_f\frac{1}{2}\rho\frac{\pi D^2}{4}\right)vv_x(x,y) \tag{7.1}$$

$$ma_y(x,y) = QE_y(x,y) - \left(C_f\frac{1}{2}\rho\frac{\pi D^2}{4}\right)vv_y(x,y) + mg \tag{7.2}$$

The equation of motion described by the equation system is solved using a finite difference method:

$$\begin{aligned} v_{n+1} &= v_n + a_n \cdot \Delta t \\ p_{n+1} &= p_n + v_{n+1} \cdot \Delta t \end{aligned} \tag{8}$$

where a_n, v_n and p_n respectively represent the vectors acceleration, velocity and position at the time $n{\cdot}\Delta t$.

Fig. 3 shows typical trajectories plotted by the simulation program. In a first series of simulations, the trajectory of a particle is calculated for fixed values of the charge/mass ratio (Fig. 3a): 10 nC/g; 7.5 nC/g; 5 nC/g; 2.5 nC/g. The obtained results show that increasing the ratio Q/m causes an increase in the horizontal deflection of the particle with respect to the symmetry axis of the separator. The particle having a charge per mass ratio 10 nC/g collides with the electrode of the installation at the point (x, y) = (-0.142 m, −0.742 m). The horizontal deflection of the particles equals −0.206 m for 7.5 nC/g; −0.139 m for 5 nC/g and −0.069 m for 2.5 nC/g. In this simulation the maximum value of the horizontal deflection is obtained with charge/mass ratios of the order of 7.5 nC/g. To avoid particle-electrode collisions, the charge should be less than this value that can be predicted by numerical simulation.

The results of the calculation of particles trajectories for different values of potential difference ΔU applied to the electrodes (20 kV; 40 kV and 60 kV), are given in Fig. 3b. They show that the increase of the potential difference ΔU causes an increase of the particles deviation with respect to the symmetry axis of the installation. The deviation varies from −0.046 m for ΔU = 20 kV, to −0.137 m for ΔU = 60 kV.

An increase of the potential difference ΔU is desired to obtain a good separation. However, an excessive increase of ΔU in the presence of particles characterized by a high Q/m ratio may cause collisions between particles and electrode that affect the quality of the product recovered at separator outlet. It should be noted also that excessive increase of ΔU may cause air breakdown in the inter