Crucial factors of plastic mixtures separation in free-fall electrostatic separator: simulation and experimental testing

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***Abstract*—Key design and operation parameters of free-fall electrostatic separator for plastic mixtures will be discussed based on the theoretical analysis, numerical investigation and also experimental testing on laboratory prototype. Major goal of presented research is to study crucial factors affecting separation of freely falling electrically charged particles between high voltage electrodes, formulate appropriate mathematical model and finally propose efficient algorithm for its numerical solution. The critical design parameters are than determined by sensitivity analysis and robust multi-objective optimization is used for design of industrial prototype for continuous separation of millimeter-size particles of plastic waste.**

I. Introduction and Motivation

Electrostatic separation of plastic/plastic mixtures in the free-fall electrostatic separator has been the subject of many research articles in both directions, theoretical and also experimental [1] - [3]. Many prototypes have been designed, tested and also used in practice, however, separator design and operation is commonly based on experimental investigation because of stochastic character of separation process. Therefore, model-based approach of process analysis is being investigated [4], [5]. Recently, Labair et al. study mathematical model and validate numerical results with experiments [6].

The purpose of the presented research and development is to discuss, formulate and analyze appropriate mathematical model which will describe, as accurately as possible, the operation of free-fall electrostatic separator. Main attention is paid to stochastic characteristics of the particles properties (electric charge, mass, initial position and velocity), multiple particles motion with both field-to-particle and particle-to-particle interactions, particles impacts on electrodes and also influence of environmental parameters (humidity and temperature) and also particle mixture characteristics. Formulated mathematical model and proposed numerical algorithm for its solution allow predict efficiency η of the separation process and purity θ of final products.

II. Description of Technical Problem

The basic principle of the free-fall electrostatic separator for plastic/plastic mixtures is based on the Coulomb force acting on freely falling particles charged by triboelectric effect. Particles of different materials accept different amount of charge (positive or negative), which depends on their positions in the triboelectric series [3].

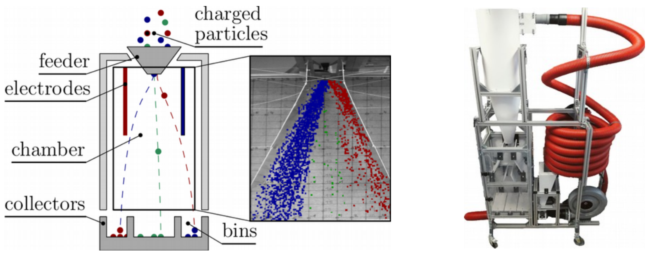

Fig. 1. Basic arrangement of free-fall electrostatic separator together with visualization of real separation process captured by high-speed camera (left figure). Photography of industrial prototype of electrostatic separator for continuous separation of millimeter-size particles designed on the base of presented results (right figure).

During the separation process, charged particles freely falling into the gap between high-voltage electrodes where the trajectories of the individual particles start being influenced by the electric field. Particles are than separated from mixture based on amount of acquired charge. Basic arrangement and principle of free-fall separator is depicted in Fig. 1 together with visualization of separation process of PVC (polyvinyl chloride) and PS (polystyrene) granular mixture.

III. Basic Discussion of Physical Model

Basic physical model of separation process is illustrated on Fig. 2. The gravity force $\boldsymbol{F}_{\mathrm{g}}$, of course, has the greatest influence on particles motion and their movement through electrode system is slowed down only by the aerodynamic drag force $\boldsymbol{F}_{\mathrm{a}}$. The shape of each particle and its size are usually strongly variable (mixture is obtained by crushing) and for the purpose of simulation it should be assumed that each particle is a variable sphere with mass density ρ and radius r defined by the normal distribution $N(\mu_{\mathrm{r}}, \sigma_{\mathrm{r}})$, where μ_{r} and σ_{r} stand for raw and central moment.

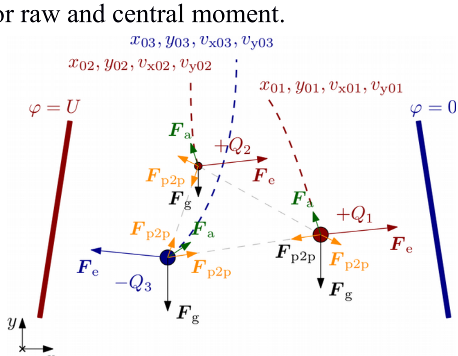

Fig. 2. Basic illustration of discussed physical model. Figure shows forces acting on the particles moving through to high-voltage electrodes.

The falling particles with electric charge Q are deflected from the trajectory by Coulomb's force $\boldsymbol{F}_e$ which is induced by external electric field $\boldsymbol{E}$ generated by the electrodes. Whereas direction of the force $\boldsymbol{F}_e$ acting on each particle of same material is related to its polarity, size of the force corresponds with amount of the particle charge Q given by normal distribution $N(\mu_Q, \sigma_Q)$. Trajectory of any particle with charge Q_i is also influenced by other charged particles with charge Q_j moving at the same time through electrode system. Particle-to-particle force $\boldsymbol{F}_{p2p}$ strongly depends on the distance d between the individual particles or rather on distance d_{avg} which describes the average distance between particles in the uniform flow.

Mutual particles collisions in the course of their movement through the chamber can be neglected in most cases. On the other hand, their collisions with the electrodes are very common and have to be reflected in the model. In the case of millimeter-size particles, where gravity force $\boldsymbol{F}_g$ is dominant, effects of electric adhesion force and also charge transfer between particles and electrodes can be neglected. This assertion is based on experiments with different plastic materials. In general case, the coefficient of restitution e can be than used for modeling of particle collision with flat electrodes.

IV. Selected Numerical Results

Based on the theoretical analysis, numerical experiments and experimental observation on laboratory prototype, a mathematical model for charged plastic particles movement in free-fall electrostatic separator was formulated. Numerical solution of mathematical model is carried out by higher-order finite element method and solution of N-body dynamics is performed by *the* Runge-Kutta method with adaptive time step.

For illustration of formulated model solution, Fig. 3 shows the simulation results of the separation process for PVC/PS mixture. Raw and central moments of electric charge distribution were estimated on the base of measurement and major parameters of experimental mixture are listed in Table I.

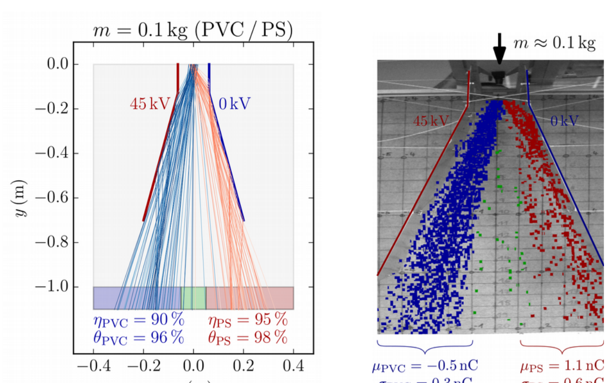

Fig. 3. Simulation results of the separation process for PVC/PS mixture (50 % of PVC and 50 % of PS). Left figure shows results of N-body simulation performed for 120 particles with total mass of mixture being 0,1 kg. Right figure shows visualization of high-speed record of separation process for PVC/PS mixture (total mass of mixture corresponds with simulation).

TABLE 1: COMPARISON OF QUANTITATIVE RESULTS OF THE EXPERIMENTS (EXP.) AND NUMERICAL SIMULATION (SIM.).

	PVC (exp.)	PVC (sim.)	PS (exp.)	PS (sim.)
η	94 %	90 %	93 %	95 %
θ	98 %	96 %	98 %	98 %

V. METHODS AND ALGORITHMS

The study was performed by comparison of numerical experiments with high-speed camera measurement of particle motion through the electrode system. On the base of study results, coupled mathematical model of electrostatic field and adaptive numerical algorithm for model solution is than proposed and verified by experimental measurement of separation process purity and efficiency. All experiments were performed on laboratory prototype depicted in Fig. 4.

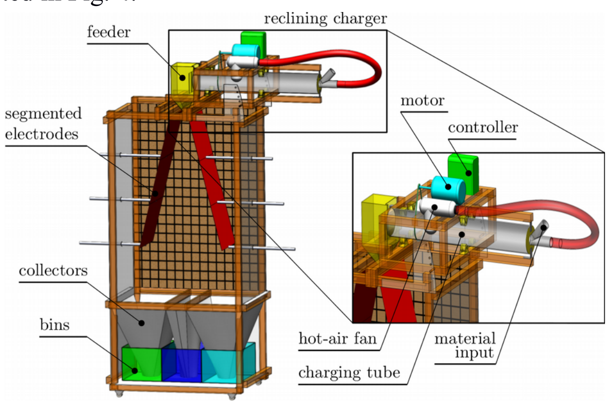

Fig. 4. Basic arrangement of laboratory prototype of free-fall electrostatic separator.

A. Measurement methods

The movement of the particles through the the electrode system (see Fig. 3) was recorded by a high-speed camera. Captured frames were post-processed by a simple particle detection algorithm, which uses a pixel-based addition of masked difference of consecutive frames (see Fig. 5).

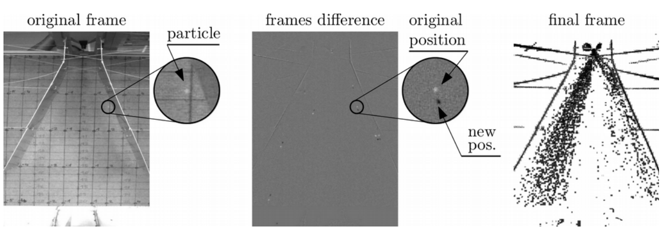

Fig. 5. Illustration of basic particle detection algorithm.

The positions of the particles are corrected with the respect to the camera position and current position of each particle and its velocity is calculated. Normal distribution $N(\mu_Q, \sigma_Q)$ of particle charge Q_p is than estimated indirectly, by comparison of numerical solution and measurement of single particle deflections from the free-fall trajectory.

B. Numerical algorithm

The proposed algorithm implements adaptive time steps for effective solution of the discussed *N*-body problem. The algorithm uses next step conditions, which are defined on the base of a step error estimated for high order (H) and lower order (L) solution of motion equations. The relative errors for the position step ε_{pos} and velocity step ε_{vel} are described individually. The algorithm indicates fast particles because of space-time coupling of the described problem.

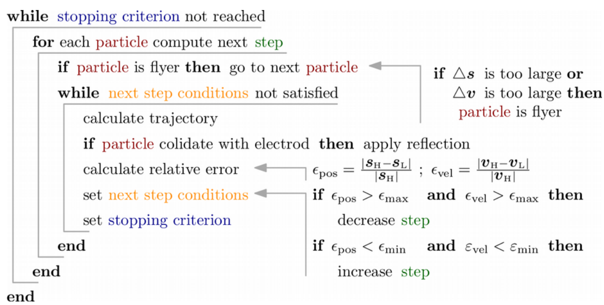

Fig. 6. Implemented adaptive particle tracing algorithm.

VI. Acknowledgment

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