Experimental Modeling of the Tribo-aero-electrostatic Separation of Mixed Granular Plastics

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***Abstract*— Experimental design methodology was employed for the optimization of the tribo-aero-electrostatic separation process that takes place in a parallelepiped fluidized bed. Two opposite walls of this device consist of metallic plates connected to two DC high-voltage supplies of opposite polarities, so that the charged particles be attracted to these electrodes and separated while still in fluidized state. The particles are then collected in two recipients each placed on a balance, to allow instantaneous mass measurement of the separated products. The mass flow rate, the voltage applied to the electrode system, and composition of feed material were the three process variables investigated. The results of full and composite-factorial experimental designs were analyzed with the commercial software MODDE 5.0. Higher voltages applied to the electrode system do not necessarily lead to larger quantities of collected products but improve the purity of the concentrates. The composition of the mixture influences the outcome of the process.**

I. INTRODUCTION

Tribo-electrostatic separation has already proven its effectiveness in recycling the constituents of the various types of granular plastic mixtures generated during the processing of waste electronic and electric equipment (WEEE) [1-4]. In practically all existing industry applications of this technology, the WEEEs are tribocharged using vibrating or cyclone-like devices, prior to exposing them to the action of the electric field forces in free-fall electrostatic separators [5].

In a series of laboratory studies, tribocharging was achieved using fluidized-beds characterized by elevated air velocities and height/diameter ratios, which favor more frequent granule-to-wall collisions [6]. By conveniently choosing the wall materials in accordance with the triboelectric series [3], a highly-efficient charging can be obtained at rather low energy expense [7]. More recently, the authors examined the possibility to improve the efficiency of the separation, by separating the charged particles in an electric field orthogonally oriented to the direction of the fluidization air [8, 9].

The aim of the present paper is to point out how such a tribo-aero-electrostatic separation process can be oprimized by using the experimental design methodology [10].

II. FLUIDIZED BED TRIBOCHARGING DEVICE

The experimental device (Fig. 1.) consisted in a rectangular prism chamber (115 mm x 85 mm x 400 mm), with two opposite vertical walls made of polycarbonate, the other two consisting in Aluminum plates connected to two adjustable DC high-voltage supplies of positive and negative polarity (models ES60P-20W and ES60N-20W, Gamma High Voltage Research Inc, Ormond Beach, FL).

The fluidization air is introduced through a perforated plate at the bottom of the chamber. The speed of the air is measured at the upper limit of the chamber and can be adjusted by a pressure regulator (up to 4 bar).

The granular material is introduced through a gutter at the top of the triboelectrification chamber by a vibratory feeder. In the fluidized bed generated by the ascending air, multiple particle-particle and some particle-wall collisions take place. The charged granules are attracted to the electrodes of opposite polarities and exit the chamber through the two gaps under the electrodes thus falling into the two dedicated recipients. The mass of the products is measured in a continuous manner with electronic balances (resolution: 0.01 g) positioned under the recipients and connected to a computer via two RS232 connectors.

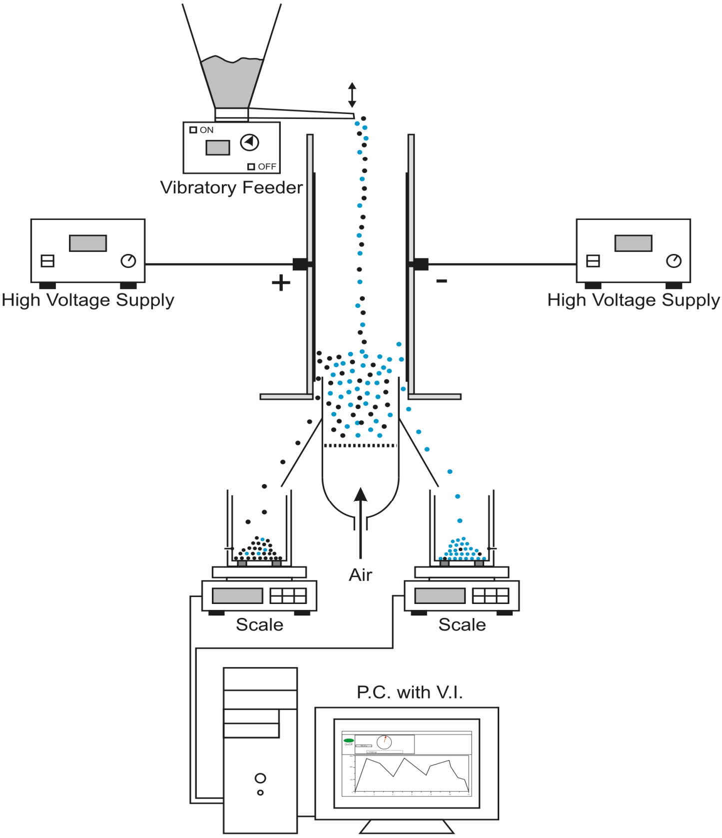


Fig. 1. Schematic representation of the experimental set-up.

III. MATERIALS AND METHOD

The tribo-electrostatic separation experiments were performed on blue virgin polyamide (PA) and orange polycarbonate (PC) granules, used in the plastics industry. Two types of samples (mass of a sample: 100 g) were prepared as binary mixtures with different compositions.

The experiments were carried out under relatively stable ambient conditions: temperature T = 17 - 22°C, relative humidity RH = 30 - 40%, and at given air velocity $v = 6$ m/s.

The mass measurement data acquired by the electronic balances during the steady-state operation of the tribocharger were processed by a virtual instrument (VI) developed in the LabView environment. The high voltage U applied to the electrodes and the mass flow rate D of the tribocharging were the two process variables investigated. The effects of each variable on the output of the process (i.e. the charge/mass ratio of the granules collected at the electrodes), were evaluated for three classes of binary granular mixtures: 50% PA – 50% PC; 70% PA – 30% PC; and 30% PA – 70% PC.

The tribocharging efficiency was analyzed by measuring the purity of the particles collected at the two electrodes of the experimental device. As a general rule, the PA granules having a positive charge were deviated towards the negative electrode and the PC particles were collected at the positive electrode. The analysis of tribo-charging results was facilitated by the fact that the two materials also differ in color.

When the objective is the optimization of a process, experimental design methodology [10, 11] recommends the adoption of a quadratic model:

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_{11} x_1^2 + a_{22} x_2^2 + a_{12} x_1 x_2 \, ; \qquad (1)$$

where y is the process response and x_i is the normalized centered value for each factor u_i:

$$x_i = (u_i - u_{ic})/\Delta u_i = u_i^*, \qquad (2)$$

with

$$u_{i\,\mathrm{c}} = (u_{i\,\max} + u_{imin})/2; \; \Delta u_i = (u_{imax} - u_{imin})/2. \qquad (3)$$

For the factors considered hereafter, i.e. the feed rate D and the applied high-voltage U, the quadratic model of the response m (and in some cases the purity p), i.e. the mass of each collected material, will take the following form:

$$m = a_0 + a_1 D^* + a_2 U^* + a_{12} D^* U^* + a_{11} D^{*2} + a_{22} U^{*2} \qquad (4)$$

In order to obtain such a quadratic model, the composite design was employed for the present study [10], [11]. The experimental data were analyzed with MODDE 5.0 software (Umetrics, Sweden) [12], which calculates the coefficients of the mathematical model, draws the response contours and identifies the best adjustments of the parameters for optimizing the process. Moreover, the program calculates two statistical criteria: the goodness of fit: R^2, and the goodness of prediction: Q^2. The latter is a measure of how well the model will predict the responses for new experimental conditions. A good mathematical model has criteria R^2 and Q^2 with the numerical value closes to the unit.

A preliminary set of experiments was carried out with a mixture of 50% PA – 50% PC, in order to determine the minimal and the maximal values of the feeding rate and of the voltage to be applied to the electrodes.

The objective of the second set of electrostatic separation tests was to assess the tribo-charging feasibility of a binary granular mixture of 50% PA – 50% PC. The tests were carried out for a duration $t = 60$ s, with the material continuously fed at a rate ranging between 3 and 9 g/s and at a potential difference between the electrodes $U = \{20;\ 26;\ 32\}$ kV following the composite design proposed by MODDE.

The third and forth electrostatic separation tests were conducted in the same way as the second, the only difference being the composition of the granular mixture: 70% PA – 30% PC respectively 30% PA – 70% PC.

A fifth and last set of experiments were carried out in the central point of the composite design in order to quantify and compare the purity of the separated materials for different granular mixtures of the feeding material.

IV. RESULTS

A. Determining the optimal feeding rate and applied voltage

Preliminary experiments showed that a voltage difference higher than 30 kV may cause corona discharges thus compromising the purity of the separated material. In this case, the search for the minimal voltage that can sustain the separation process was made through a series of experiments on a granular mixture comprised of 50% PA and 50% PC at a fixed feeding rate. The separation process was interrupted after 60 seconds and the purity of the separated material was evaluated by manual sorting of the collected particles.

These experiments were conducted at several applied voltages (between 12 and 20 kV each polarity in increments of 2 kV) as presented in Fig. 2. The aim of the separation process is to have two materials with a purity superior of 95%. Therefore the minimal voltage value that is to be used in the quadratic models has been chose as the first voltage value that a purity superior of 95% was measured, i.e. 20 kV (±10 kV).

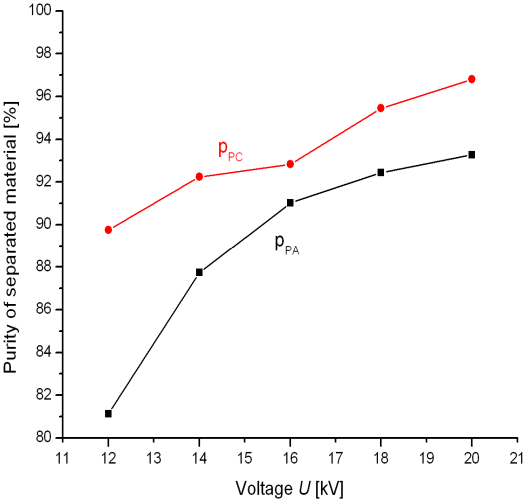


Fig. 2. Purity of separated PC and PA versus applied voltage U.

The feeding rate was chosen around a central value based on empirical evidence determined by experimental tests carried out at a fixed air flow rate. The maximum was defined as the highest value of the feeding rate where material overflow does not occur. The maximal value of the feeding rate was observed at 9 g/s and the central value at 6 g/s. In this case the minimal value was chosen at 3 g/s in order to have a symmetrical interval of variation.

B. The composite factorial experimental design for a granular mixture of 50% PA – 50% PC

First composite design was conducted with a granular mixture of 50% PA – 50% PC for a duration of 60 s, the material being fed continuously at a rate *D* [g/s]. The measured mass and purity of each separated material were recorded at different values of voltage and feed rate as proposed by MODDE (Table 1).

TABLE 1: PURITY OF PA AND PC COLLECTED GRANULES, FIRST COMPOSITE FACTORIAL EXPERIMENTAL DESIGN

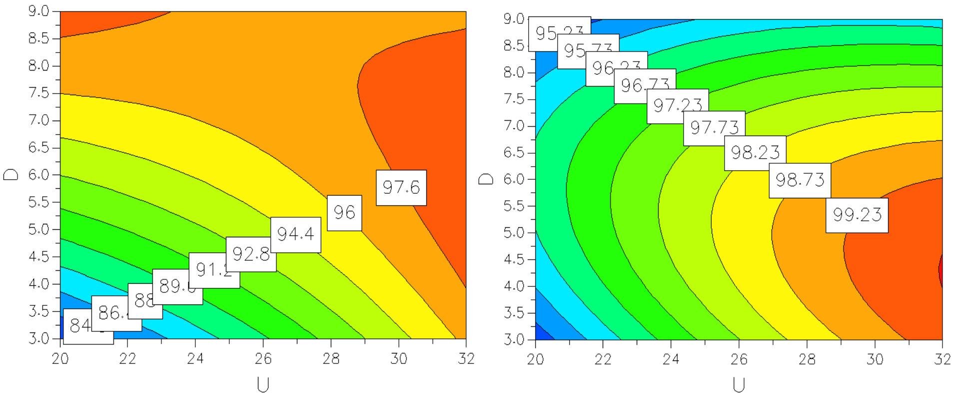
Run number	Feed rate D [g/s]	Voltage U [kV]	Purity p_{PC} [%]	Purity p_{PA} [%]
1	3	20	94.7	82.3
2	9	20	94	97.7
3	3	32	99.6	96.5
4	9	32	95.6	97.8
5	3	26	97.8	90.2
6	9	26	97	97.2
7	6	20	97.3	94.2
8	6	32	99.5	98.2
9	6	26	97.8	94.8
10	6	26	98.8	95.3
11	6	26	97.2	95.6

The mathematical models of the responses p_{PC} (goodness of fit $R^2 = 0.858$, goodness of prediction $Q^2 = 0.103$) and p_{PA} ($R^2 = 0.977$, $Q^2 = 0.781$) were:

$$p_{\mathrm{PA}}\,[\%] = 95.46 + 3.95\,D^* + 3.05\,U^* - 2.1\,D^{*2} + 0.39\,U^{*2} - 3.52\,D^*U^* \quad (5)$$

$$p_{\mathrm{PC}}\,[\%] = 98.33 - 0.91\,D^* + 1.45\,U^* - 1.52\,D^{*2} - 0.53\,U^{*2} - 0.82\,D^*U^* \quad (6)$$

According to these models, the purity of the separated materials range between 84% and 99.2 % with higher values in the case of PC (Fig. 3.). The maximal value for PA is observed ar higher values of both feed rate and voltage. In the case of PC the best results are obtained for highest applied voltage and for lowest values of feed rate.



(a) (b)

Fig. 3. MODDE 5.0 predicted equal purity contours for p_{PA} (a) and p_{PC} (b), the flow rate D and high voltage U are expressed in [g/s] respectively [kV].

The lower purities for PA can be explained by the fact that the size and mass of each PC granule is smaller that of a PA granule and thus easier for the airflow to move slightly more particles in the collecting zone of PA granules. In spite of the increased voltage applied to the electrodes, gravity and aerodynamic are greater that the electrical forces and the granules do not have sufficient time to move out of that zone. It is inevitably collected and counted as impurity even if it’s charged with the opposite polarity that the rest of the particles.

C. Composite factorial experimental designs for non-balanced mixtures of material: 30% PA – 70 % PC and 30% PC – 70 % PA

The results of the experiments carried out on 11 samples for each mixture are given in Table 2.

They show that in some cases, the purity of the collected material is greater than 99%. In the case of 30% PA – 70 % PC mixture, the purity of PC, is almost 100% thus making a model futile, because the value is a constant. The same mention can be made for PA in the case of a 30 % PC – 70 % PA granular mixture.

The values of purity for the minority materials in the granular mixture are not sufficiently good after the separation process (51.9% to 85.4%).

These values can be explained by the fact that the minority material can charge only a part of the majority material (that is collected with purity close to 100%) while the other part is being collected at the other electrode, along the material found in the initial mixture in minority.

D. Experiments on other non-balanced mixtures: 80% PA – 20% PC, 80% PC – 20% PA, 60% PC – 40 % PA and 60% PA – 40 % PC

The results of the Table 2 conducted to a new series of experiments that were carried out with other non-balanced mixtures at fixed values of feed rate and applied voltage: 6 g/s respectively 26 kV.

TABLE 2: PURITY OF PA AND PC COLLECTED GRANULES, SECOND AND THIRD COMPOSITE FACTORIAL EXPERIMENTAL DESIGN

Run number	Feed rate D [g/s]	Voltage U [kV]	30% PA – 70 % PC		30% PC – 70 % PA	
			Purity p_{PC} [%]	Purity p_{PA} [%]	Purity p_{PC} [%]	Purity p_{PA} [%]
1	3	20	>99	64	75.5	>99
2	9	20	>99	84	62.3	>99
3	3	32	>99	85.4	60	>99
4	9	32	>99	84.7	68.4	>99
5	3	26	>99	77	78.6	>99
6	9	26	>99	85.5	52.2	>99
7	6	20	>99	81.1	51.9	>99
8	6	32	>99	81.5	53.1	>99
9	6	26	>99	73.96	63.2	>99
10	6	26	>99	54.3	68.2	>99
11	6	26	>99	63.1	62.3	>99

The outcome measured was in each case the purity of the separated materials, as shown in Fig.4.

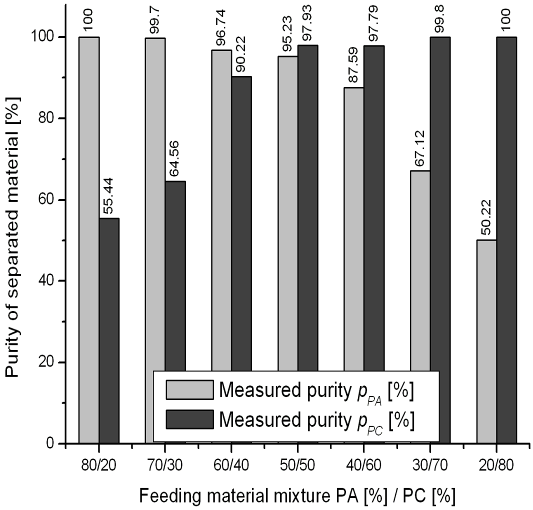


Fig. 4. Purity of separated PA and PC at different compositions of granular mixture.

The purities of the separated materials reach a maximum in the case of a balanced mixture. The more unbalanced is the mixture, the lesser is the purity obtained for the minority material while the majority material has purity close or equal to 100%.

V. CONCLUSION

Tribocharging of granular plastic mixtures in fluidized beds is a multi-factorial process. The purity of the separated materials strongly depends on the granular mixture of the material that is to be separated.

The best values of purity are obtained for both material in the case of a balanced mixture at higher values of applied voltage and lower values of feed rate.

In the case of a non-balanced mixture one of the separated materials have purity close to 100% and can be used as it is, while the other is collected with purity closer to 50% and can be further separated with better results.

The mass and geometry of each particle has to be similar as the process of separation needs to be as homogenous as possible.

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