Optimisation of belt-type electrostatic separation of granular plastic mixtures tribocharged in a propeller-type device

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Abstract. Electrostatic separation has already proven its efficiency as a method to recover metals and plastics from granular waste electrical and electronic equipment (WEEE). Nevertheless, there still is some work to do regarding the sorting of the various sorts of plastics (ABS, ABS-PC, HIPS, PC) contained in information technology wastes. The main objective of this paper is to optimize the electrode configuration and the operation of a belt-type electrostatic separator employed in conjunction with a new tribo-aerodynamic charging device. This application is particularly designed for the recovery of granular materials issued from shredding of computer cases, which contain large quantities of ABS. The following control variables were considered for the optimization: (i) distance between the axis of the high-voltage electrode and the surface of the grounded belt electrode; (ii) angular position of the high-voltage electrode with respect to the horizontal plane; (iii) high-voltage level. Experimental design methodology was employed for determining the optimum value of each variable, using commercial software (MODDE, Umetrics, Sweden).

1. Introduction
The recycling of materials contained in waste electrical and electronic equipment (WEEE) is an important issue for the sustainable use of natural resources [1]. Electrostatic separation, which is the generic term given to sorting of granular mixtures by making use of the electrical forces acting on charged or polarized bodies [2, 3], has already proven its efficiency to recover metals and plastics from chopped WEEE [4, 5]. Nevertheless, there still is some work to do regarding the sorting of the various sorts of plastics (ABS, ABS-PC, HIPS, PC) contained in information technology wastes. In most of the existing plastic – plastic electrostatic separation technologies, the granular mixtures are first processed in a tribocharging device [6], and then introduced in the electric field generated between two vertical plate electrodes. The efficiency of tribocharging being affected by a number of uncontrolled factors (ambient temperature and relative humidity, particle surface state, etc.), the free-fall plastic/plastic tribo-electrostatic separators [7, 8] are not as effective as the role-type corona-electrostatic equipment employed for the sorting of plastic/metal mixtures.

The work presented in this paper was aimed at optimizing the electrode configuration and the operation of a belt-type electrostatic separator employed in conjunction with a new tribo-aerodynamic charging device [9]. The study focused on the recovery of granular materials issued from shredding of computer cases, which contain large quantities of ABS. Experimental design methodology was employed for the evaluation of the various factors and the estimation of their optimal values.

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2. Experimental set-up

The experiments were carried out using a belt-type tribo-electrostatic separator (Fig. 1, a) consisting of a custom-designed tribocharging device, a vibratory feeder, a metallic conveyor (roll diameter=5cm), connected to the ground, an elliptical electrode (axis: 15 cm and 5 cm), energized from a fully-adjustable DC high voltage power supply (40 kV; 1 mA) and a three-compartment collector of particles: two boxes for the pure products and one for the middling. The granular mixture to be separated is introduced in the tribocharging device, which consists of a cylindrical tube made of PVC (diameter: 10 cm; height: 35 cm) and a coaxial plastic propeller inside it (Fig. 1, b). The optimum operation of this device, i.e. propeller speed \( v = 3533 \text{ RPM} \) and duration \( t = 40 \text{ s} \) of the tribocharging, has been established based on the experimental data reported in a previous paper [9].

![Figure 1. Schematic representation of the belt-type tribo-electrostatic separator (a) and of the propeller-type tribocharging device (b).](image)

The tribocharged materials are then deposited by gravity on the tray of a vibratory feeder that transfers them at a constant rate on the metallic belt of a variable-speed conveyor, entrained by a DC motor. The feed-rate and the speed of the conveyor are co-related, so that the material to form a monolayer at the surface of the belt.

The conveyor introduces the particles in the electric field zone generated between the high-voltage electrode of positive polarity and the grounded belt. The negatively-charged particles are subjected to an attraction force exerted by the electrode of opposite polarity, while the positively-charged ones are pinned to the surface of the belt, until a brush will mechanically remove them, as shown in Fig. 1, a. Based on the results of several preliminary experiments, the high voltage electrode was positioned at \( h = 7 \text{ cm} \) above the plane of the belt, while the speed of the DC motor drive was adjusted at 15 RPM.

3. Materials and method

The 10 g samples used for the experiments consisted in a granular mixture of 50% white ABS and 50% black HIPS (size distribution: 1 mm to 2 mm). After each experiment, the masses of the collected products were measured with an electronic balance (resolution: 0.01 g).

Using the experimental design methodology [10], the quadratic model was obtained for each of the responses \( y_{\text{ABS}} \), \( y_{\text{HIPS}} \), \( y_{\text{Mixture}} \) i.e. the mass of the three collected products, as function of the normalized centred values \( u_i^* \) of each factor \( u_i \) considered in the present study, i.e. the applied voltage \( U \), the angle \( \alpha \) and the horizontal position \( d \) of the electrode:

\[
y = a_0 + a_1 U^* + a_2 d^* + a_3 \alpha^* + a_{11} U^* U^* + a_{33} \alpha^* \alpha^* + a_{12} U^* d^* + a_{23} d^* \alpha^* + a_{13} \alpha^* U^* \quad (1)
\]

\[
u_i^*=(u_i - u_{ic})/\Delta u_i; \quad u_{ic}=\frac{(u_{imax}+u_{imin})}{2}; \quad \Delta u_i=\frac{(u_{imax}-u_{imin})}{2}. \quad (2)
\]

In order to obtain such a quadratic model, the data of a composite factorial experiment (Table I) data were analysed with MODDE 5.0 software (Umetrics, Sweden), which calculates the coefficients of the mathematical model, draws the response contours and identifies the best adjustments of the parameters for optimizing the process.
4. Results and discussion

4.1. Domain of variation of the control variables

All the experiments were performed at temperatures ranging between 20.2°C and 23.3°C, while the relative humidity varied between 37.2% and 41.3%. Three sets of "one-factor-at-a-time" experiments were performed in order to establish the domain of variation of the control variables. In the first set, the applied voltage was adjusted at various values between 5 and 25 kV, while the other two variables were kept constant: $\alpha = 30^\circ$, $d = 7$ cm. The results are illustrated by the curves in figure 3, where each point is the average value of at least three experiments. At voltages higher than 15 kV, more than 80% of the ABS and HIPS particles in the feed are recovered in the final products. The lower value of the HIPS mass at 25 kV can be explained by the strong electric field forces that made some of the particles impact the high-voltage electrode and be deviated in the ABS compartment.

For the second set of experiments $\alpha = 30^\circ$, $U = 15$ kV and the horizontal position $d$ of the static electrode was adjusted between 5 and 7 cm (Fig. 2, b). Slightly smaller quantities of HIPS were collected at $d = 7$ cm, but the process is quite robust with respect to this factor. This effect is due to the modification of the electric field distribution. At higher values of $d$, the reduction of the local strength of the electric field is accompanied by a diminution of the electric forces acting on the HIPS particles, which will detach sooner from the surface of the belt and be collected in the middling compartment. In the third set of experiments, the angular position $\alpha$ of the static electrode was varied between 20° and 60°, at constant $U = 15$ kV and $d = 7$ cm (Fig. 2, c). At $\alpha > 30^\circ$, the quantity of HIPS diminishes, for reasons similar to those given for the variation of $d$. Based on the above data, the domain of the variables was established as follows: $U = 15$ to 25 kV; $\alpha = 20$ to 30°; $d = 5$ to 7 cm.

4.2. Modeling and optimization of the separation process

The mathematical models of the responses $y_{\text{HIPS}}$ ($R^2 = 0.999$; $Q^2 = 0.994$) and $y_{\text{ABS}}$ ($R^2 = 0.997$; $Q^2 = 0.983$), and were obtained with MODDE 5.0 using the data in Table 1 (the non-significant coefficients were eliminated):

$$y_{\text{HIPS}} = 5.02 + 0.045 U^* + 0.067 d^* + 0.134 \alpha^* - 0.0016 U^* \alpha^* - 0.14 d^* \alpha^* + 0.104 U^* d^* - 0.0098 U^* \alpha^* - 0.037 d^* \alpha^*$$

$$y_{\text{ABS}} = 4.58 - 0.039 U^* - 0.139 d^* - 0.034 \alpha^* + 0.072 U^* \alpha^* + 0.107 d^* \alpha^* + 0.04 \alpha^* + 0.037 U^* d^* + 0.018 U^* \alpha^* + 0.0197 d^* \alpha^*$$

The two statistical criteria computed by MODDE 5.0 were excellent (i.e., close to unity) for both models: the goodness of fit $R^2 = 0.999$ and 0.997; the goodness of prediction $Q^2 = 0.994$ and 0.983. The predicted mass of collected ABS is represented in Fig. 3. Similar curves were obtained for $y_{\text{HIPS}}$. 

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**Figure 2.** Mass of the products obtained from 10-g samples of 50% ABS – 50% HIPS, as function of: (a) the applied voltage $U$, for $\alpha = 30^\circ$, $d = 7$ cm; (b) the horizontal position $d$, for $\alpha = 30^\circ$, $U = 15$ kV; (c) the angular position $\alpha$, for $U = 15$ kV; $d = 7$ cm.
Table 1. Masses of the products obtained from a 5g HIPS + 5 g ABS granular mixture, using a composite factorial experimental design

| N° | $U$ [kV] | $d$ [cm] | $\alpha$ [$^\circ$] | HIPS [g] | Middling [g] | ABS [g] |
|----|---------|---------|----------------|---------|-------------|--------|
| 1  | 15      | 5       | 20             | 4.26    | 0.46        | 5.2    |
| 2  | 25      | 5       | 20             | 4.10    | 0.72        | 5.17   |
| 3  | 15      | 7       | 20             | 4.23    | 0.81        | 4.9    |
| 4  | 25      | 7       | 20             | 4.71    | 0.67        | 4.64   |
| 5  | 15      | 5       | 40             | 4.77    | 0.29        | 5.02   |
| 6  | 25      | 5       | 40             | 4.35    | 0.41        | 5.09   |
| 7  | 15      | 7       | 40             | 4.49    | 0.7        | 4.84   |
| 8  | 25      | 7       | 40             | 4.89    | 0.42        | 4.67   |
| 9  | 15      | 6       | 30             | 4.98    | 0.34        | 4.71   |
| 10 | 25      | 6       | 30             | 5.09    | 0.33        | 4.61   |
| 11 | 20      | 5       | 30             | 4.72    | 0.4         | 4.95   |
| 12 | 20      | 7       | 30             | 4.86    | 0.51        | 4.64   |
| 13 | 20      | 6       | 20             | 4.57    | 0.59        | 4.67   |
| 14 | 20      | 6       | 40             | 4.92    | 0.48        | 4.58   |
| 15 | 20      | 6       | 30             | 5.02    | 0.38        | 4.6    |
| 16 | 20      | 6       | 30             | 4.99    | 0.4         | 4.57   |
| 17 | 20      | 6       | 30             | 5.03    | 0.39        | 4.61   |

Figure 3. MODDE 5.0-predicted variation of collected masses of ABS, as function of the applied voltage (a), the horizontal position (b) and the angular position (c) of the electrode. The upper and the lower curves on each graph indicate the limits of the 95% confidence interval.

MODDE 5.0 offered also the possibility of identifying the optimal point of the process: $U = 15$ kV, $d = 5.7$ cm and $\alpha = 33^\circ$, for which the predicted masses of collected products were: $y_{\text{HIPS}} = 5.02$ g and $y_{\text{ABS}} = 4.86$ g. The masses collected in an experiment conducted in the optimal conditions were $m_{\text{HIPS}} = 4.97$ g and $m_{\text{HIPS}} = 4.64$ g, in very good agreement with the predictions.

5. Conclusions
(1) The tribo-electrostatic process associating a propeller-type tribocharging device and a belt-type electrostatic separator is a promising technology for the recovery and recycling of the plastic materials contained in granular WEEE.
(2) Experimental design methodology proved to be an effective tool for the optimization of the novel tribo-electrostatic separation process.

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