Optimisation of belt-type electrostatic separation of tribo-aerodynamically charged granular plastic mixtures

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***Abstract* – The electrostatic separation is frequently employed for the selective sorting of conducting and insulating materials for waste electric and electronic equipments (WEEE). In a series of recent papers, the authors have presented several novel tribo-electrostatic separation installations for the recycling of the main categories of plastics contained in information technology wastes. The aim of the present work is to optimize the design and the operation of such an installation, composed of a belt-type electrostatic separator associated to a propeller-type tribo-charging device. The experimental design method is employed for modeling and optimizing the separation of a mixture of high-impact-polystyrene (HIPS) and acryl-butyl-styrene (ABS) granules originating from shredded out-of-use computer cases. A distinct experiment is carried out on three synthetic mixtures of virgin plastic granules: 75% polyamide (PA) + 25% polycarbonate (PC); 50% PA + 50% PC; 25% PA + 75% PC. The best results are obtained for the mixtures containing equal quantities of the two constituents.**

***Index Terms*—electrostatic separation, plastics, recycling, triboelectricity, waste electric and electronic equipment**

I. INTRODUCTION

The electric and electronic appliances (refrigerators, washing machines, mobile phones, computers, printers, TVs) have a relatively short life, due to rapid changes in equipment features and capabilities, and this creates a large waste stream of obsolete equipment [1, 2]. In the European Union, the waste electric and electronic equipment (WEEE) represent more than 10^7 tons per year, out of which up to 30% are plastics: ABS, HIPS, PA, PC [3]. The vast majority of WEEE are subject either to component recycling via disassembly; or to materials recycling via a mechanical treatment involving shredding, granulation, magnetic separation, and classification [4].

Electrostatic separation processes have been specifically developed for the selective sorting of the various types of plastics contained in the WEEE [5-8]. Several types of tribo-electrostatic separators have been specifically designed for this important class of industry applications [9, 10]. Research is in progress for developing new tribo-charging devices (vibratory, compressed-air, fluidized-bed) and improving the overall separation efficiency of the associated separation equipment [11, 12].

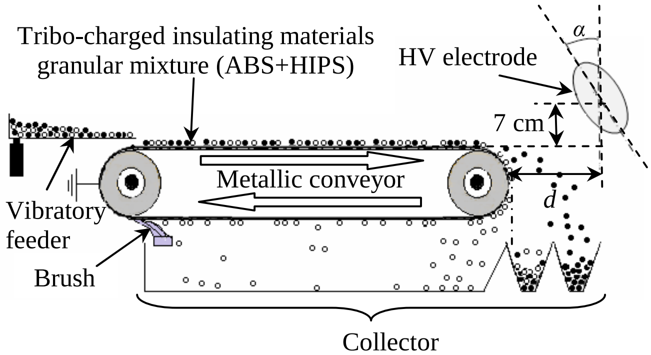


Figure 1: Schematic representation of the belt-type tribo-electrostatic separator

In a series of recent papers [13-15], the authors presented several novel tribo-electrostatic separators for the recovery of granular materials issued from shredding of computer cases, which contain large quantities of ABS and HIPS. The present work is aimed at optimizing the design and the operation of a belt-type electrostatic separator processing granular plastics tribo-charged in a propeller-type device [16]. Experimental design methodology has been employed for evaluating the effects of three control variables of the separation process of a 50% ABS + 50% HIPS granular mixture. The optimal values of the three control variables have then been used as set-point for the separation of another type of mixture, containing PC and PA granules in different proportions (75% PA + 25% PC; 50 PA + 50% PC; 25% PA + 75% PC) to simulate the diversity of the situations of practical interest.

II. EXPERIMENTAL SET-UP

The experiments were carried out using a belt-type tribo-electrostatic separator (Fig. 1) consisting in a custom-designed tribo-charging device (Fig. 2), a vibratory feeder, a metallic conveyor (roll diameter: 5 cm), 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.

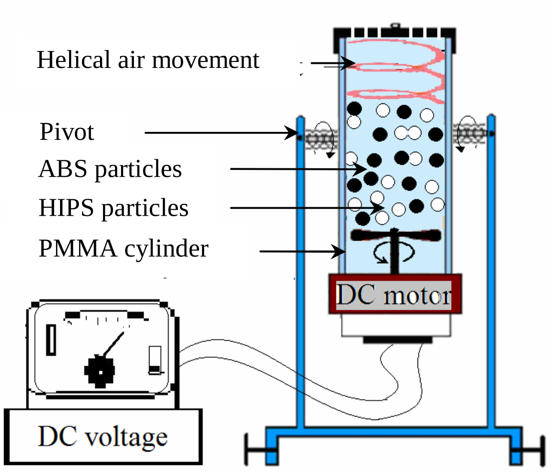


Fig. 2. Schematic representation of the propeller-type tribo-charging device.

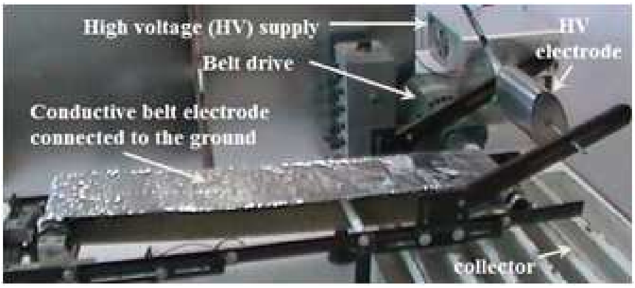


Fig. 3:.Photograph of the belt- electrostatic-separator.

The cylindrical chamber of the tribo-chaging device (diameter: 100 mm; length: 350 mm) is made of Polymethyl-methacrylate (PMMA) and is provided at its lower end with a co-axial propeller, driven by a variable-speed DC electric motor [16]. This device entrained the granular materials into a helical motion that is expected to favor their tribo-electric charging by granule-to-propeller, granule-to-cylinder wall, and granule-to-granule collisions. The sign and the magnitude of the charge of each granule are determined by the combined action of these three physical mechanisms.

When the tribocharging process is considered to be completed, the cylindrical chamber can rotate with respect to a horizontal axis and the granules can be evacuated. This operation can be performed with the propeller still in motion, so that to facilitate the recovery of all the charged granules, which might otherwise remain attached to the walls of the cylinder. 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 (Fig. 3) 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 mono-layer at the surface of the belt.

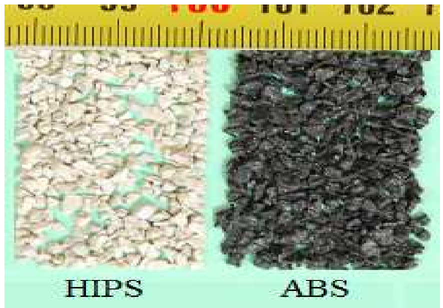


Fig. 4. Photograph of ABS and HIPS granules.

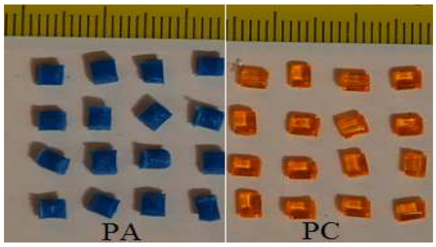


Fig.5. Photograph of PA and PC granules.

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.

Based on the results of several preliminary experiments, the high voltage electrode is positioned at h = 7 cm above the plane of the belt, while the speed of the DC motor drive is adjusted at 15 RPM.

III. Materials and Method

Two classes of samples are used for the experiments; the first granular mixture is composed of 5 g ABS and 5 g HIPS (Fig. 4; size distribution: 1 to 2 mm), originating from shredded out-of-use computer cases, provided by a WEEE recycler (APR2, France). The second class of mixtures contained PA and PC granules (Fig. 5; size distribution: 2 mm to 4 mm) in different proportions: 75% PA + 25% PC; 50 PA + 50% PC; 25% PA + 75% PC. After each experiment, the mass of the collected products were measured with an electronic balance (resolution: 0.01 g).

Using the experimental design methodology [17], the outcome y of the separation process (i.e., collected mass m) can be described by a quadratic model:

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

where x_i: normalized centred values u_i* of each factor u_i:

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

$$u_{ic}=(u_{imax}+u_{imin})/2;\ \Delta u_i = (u_{imax} - u_{imin})/2 \quad (3)$$

For the factors considered in the present study, i.e, the applied voltage U, the angle α and the horizontal position d of the electrode, the quadratic model of the responses y_{ABS}, y_{HIPS}, $y_{Mixture}$, i.e. the mass of the three collected products, , will take the following form:

$$y = a_0 + a_1U^* + a_2 d^* + a_3 \alpha^* + a_{11}U^{*2} + a_{22} d^{*2} + a_{33}\alpha^2 + a_{12} U^*d^* + a_{23} d^*\alpha^* + a_{31} \alpha^*U^* \quad (4)$$

In order to obtain such a quadratic model, the composite design was employed for the present study [17, 18]. The experimental data were analysed with MODDE 5.0 software (Umetrics, Sweden) [19], which calculates the coefficients a_i of the 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 approaching unity.

The optimal values of different factors were then used as set-point for the separation of PA + PC mixtures (sample mass: 20 g).

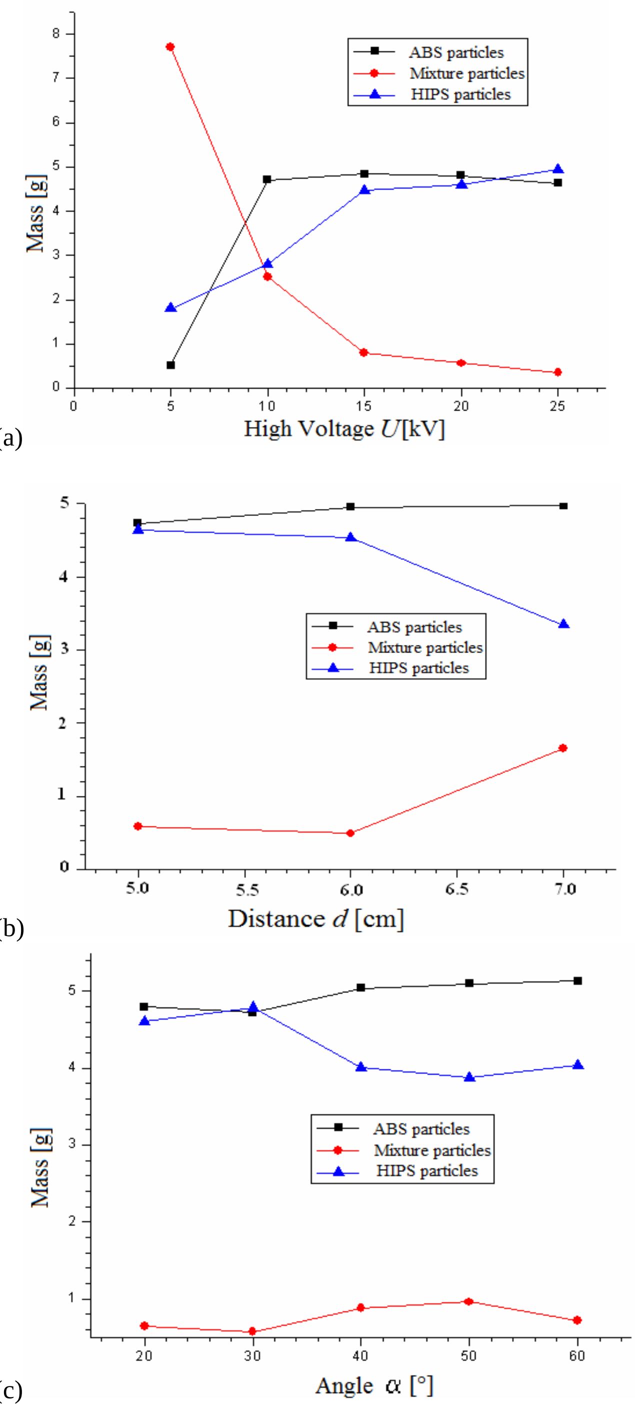
IV. Results and Discussion

A. ABS – HIPS separation

The experiments were performed at temperatures ranging between 20.2°C and 23.3°C, at an ambient relative humidity that varied between 37.2% and 41.3%. The domain of variation of the control variables was established based on the results of three sets of "one-factor-at-a-time" experiments (Fig. 6, where each point is the average value of at least three experiments). In the first set (Fig. 6, a), the applied voltage was adjusted at various values between 5 and 25 kV, while the other two variables were kept constant: α = 30°, d = 7 cm. At voltages > 15 kV, more than 80% of the ABS and HIPS particles in the feed are recovered in the final products. The lower recovery of HIPS at 25 kV is due to 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 (Fig. 6, b) α = 30°, U = 15 kV and the horizontal position d of the static electrode was adjusted between 5 and 7 cm (see Fig. 1). 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 larger 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.

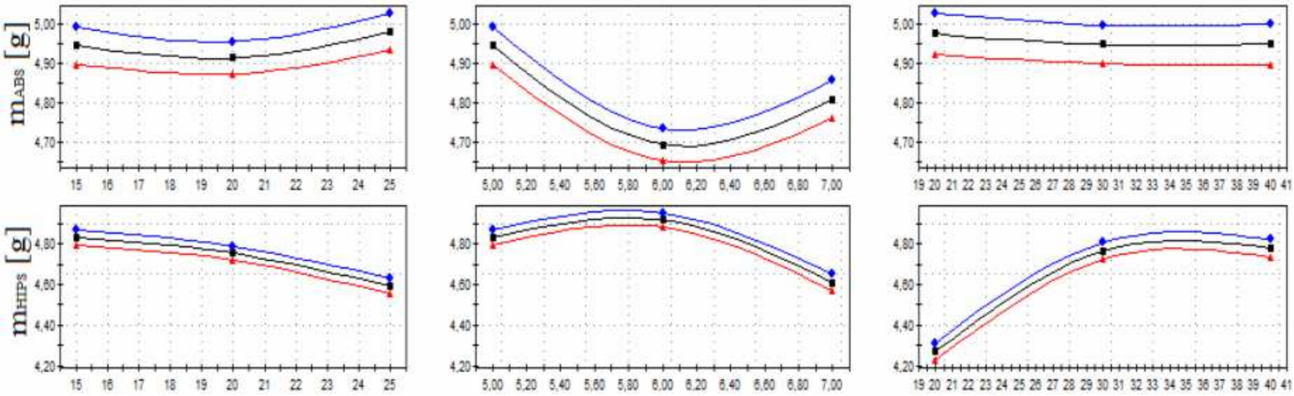
In the third set of experiments, the angular position α of the static electrode was varied between 20° and 60°, at constant U = 15 kV and d = 7 cm. At α > 30°, the quantity of HIPS diminishes, for reasons similar to those given for the variation of d.



(a) (b) (c)

Figure 6. Mass of the products obtained from 10-g samples of 50% ABS – 50% HIPS, as function of: (a) the applied voltage U, for α = 30°, d = 7 cm; (b) the horizontal position d, for α = 30°, U = 15 kV; (c) the angular positionα, for U = 15 kV; d = 7 cm.

Based on the above data, the domain of the variables was established as follows: U = 15 to 25 kV; α = 20 to 30°; d = 5 to 7 cm.



High-voltage U [kV] | Distance d [cm] | Angle α [°]

(a) (b) (c)

Fig, 7. MODDE 5.0-predicted variation of collected masses of ABS, HIPS and mixture, as function of the applied voltage U (a), the horizontal position d (b) and the angular position α (c) of the electrode. The upper and the lower curves on each graph indicate the limits of the 95% confidence interval.

TABLE I. MASSES OF THE PRODUCTS OBTAINED FROM A 5 g HIPS + 5 g ABS GRANULAR MIXTURE, USING A COMPOSITE FACTORIAL EXPERIMENTAL DESIGN

U [kV]	d [cm]	α [°]	HIPS [g]	Mixte [g]	ABS [g]
15	5	20	4,26	0,76	5
25	5	20	4,09	0,85	5
15	7	20	4,23	0,81	4,9
25	7	20	4,71	0,64	4,6
15	5	40	4,77	0,27	5
25	5	40	4,51	0,41	5
15	7	40	4,49	0,7	4,8
25	7	40	4,89	0,52	4,6
15	6	30	4,9	0,34	4,7
25	6	30	4,99	0,37	4,6
20	5	30	4,72	0,33	5
20	7	30	4,86	0,5	4,6
20	6	20	4,57	0,69	4,7
20	6	40	4,92	0,48	4,6
20	6	30	4,95	0,44	4,6
20	6	30	4,99	0,4	4,6
20	6	30	4,95	0,43	4,6

The results of the composite factorial experimental design performed in view of separation process modelling and optimization are given in Table I. The corresponding mathematical models of the responses y_{HIPS} and y_{ABS} were obtained with MODDE 5.0 and – after elimination of the non-significant coefficients – can be expressed as follows:

$$y_{HIPS} = 5.02 + 0.045\, U^* + 0.067\, d^* + 0.134\, \alpha^* - 0.0016\, U^{*2} - 0.14\, d^{*2} + 0.104\, U^* d^* - 0.0098\, U^*\alpha^* - 0.037\, d^*\alpha^* \quad (5)$$

$$y_{ABS} = 4.58 - 0.039\, U^* - 0.139\, d^* - 0.034\, \alpha^* + 0.072\, U^{*2} + 0.107\, d^{*2} + 0.04\, \alpha^{*2} - 0.037\, U^* d^* + 0.018\, U^*\alpha^* + 0.0197\, d^*\alpha \quad (6)$$

The two statistical criteria computed by MODDE 5.0 were excellent for both models: the goodness of fit $R^2 = 0.998$ and 0.991; the goodness of prediction $Q^2 = 0.991$ and 0.939.The predicted mass of collected ABS, HIPS and mixture are represented in figure 7.

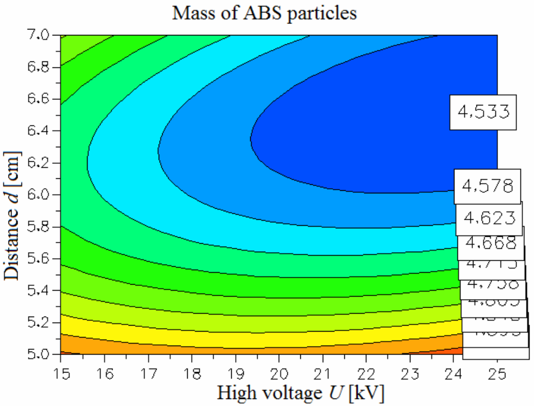
MODDE 5.0 offered also the possibility of identifying the optimal point of the process: U = 15 kV, d = 5 cm and α = 35°, for which the predicted masses of collected products were: y_{HIPS} = 4.83 g and y_{ABS} = 4.94 g (see also Fig. 8). The masses collected in an experiment conducted in the optimal conditions were m_{HIPS} = 4.64 g aand m_{HIPS} = 4.97 g, in very good agreement with the predictions.

B. PA – PC separation

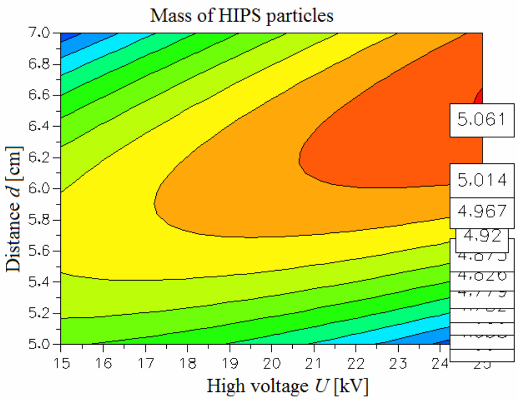
The separation of the PA –PC samples was performed in the conditions previously-established as optimal for the ABS – HIPS mixture (U = 15 kV, d = 5 cm and α = 35°). The results of the experiments are given in Table II. They demonstrate that the efficiency of the tribo-electrostatic separation depends on the proportion of PA and PC granules that compose the mixture. The best results were obtained for the balanced mixture 50% PA + 50% PC, at purities > 97%.

TABLE II: RECOVERY OF PA AND PC AFTER ELECTROSTATIC SEPARATION OF THREE DIFFERENT SAMPLES

Sample composition		Recovery after separation		
PA	PC	PA [g]	Mixte [g]	PC [g]
75% (15g)	25% (5g)	14.7	0.7	4.32
50% (10g)	50% (10g)	9.99	0.3	9.71
25% (5g)	75% (15g)	4.7	1.52	13 .74



(a)



(b)

Fig. 8. MODDE-computed equal response contours of ABS (a) and HIPS (b) recovery for α = 35°.

V. Conclusions

(1) The association of a propeller-type tribo-charging device and a belt-type electrostatic separator is an effective solution for recovery and recycle of plastics from granular WEEE.

(2) Optimization of such multi-factorial process can be successfully performed using the experimental design methodology.

(3) The efficiency of the separation depends on the composition of the granular mixture. Better results are obtained for balanced mixtures, composed of equal parts of each constituent.

(4) Further research is needed for quantifying the efficiency of this technique in the case of granular mixtures composed of more than two constituents.

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