Experimental Modelling of a New Tribo-electrostatic Separation Process for Mixed Granular Polymers

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***Abstract* -- Recycling of plastics from industrial wastes requires appropriate sorting technologies, such as the free-fall electrostatic separation of tribocharged granular materials. This paper introduces a novel electrostatic separation process characterized by the fact that the granules to be separated are charged in a fluidized bed affected by an electric field generated by two rotating roll electrodes. The experimental design methodology was employed for the modelling and optimization of the separation of a mixture composed of Acrylonitrile Butadiene Styrene (ABS) and High Impact Polystyrene (HIPS), originating from shredded obsolete computer cases. After processing the experimental data using the MODDE 5.0 software, the masses of ABS, HIPS and middling collected after separation were expressed as quadratic functions of three of the control variables of the process: (1) duration; (2) speed of the fluidization air; (3) high voltage applied to the electrode system. The obtained results demonstrate the effectiveness of this method for the separation of plastics from granular wastes.**

***Index Terms* — high voltage, electrostatic separator, tribo-electrity, waste electric and electronic equipment**

I. Introduction

Electrostatic separation technologies have been widely employed for the recycling of industrial wastes and the purification of mineral products [1-7]. The electric field forces are extremely effective in the selective sorting of corona and/or induction charged granular mixtures of conducting and insulating materials from waste electric and electronic equipment (WEEE) [8-10]. Tribocharging the granular plastics contained in the WEEEs prior to exposing them to the action of the electric field forces in a free-fall electrostatic separator is a solution that has already been validated by the recycling industry [11, 12].

During recent years, several attempts have been made to improve the efficiency of the existing technologies, which make use of vibrating or cyclone-like tribocharging devices [13-17]. In several previous paper, the authors examined the possibility of tribocharging the granular WEEEs in a fluidized bed [18-20]. In such devices, the granules get charged by colliding against each other and with the walls of the fluidized bed; then they fall freely in the electric field generated between two vertical plate electrodes energized from two high-voltage supplies of opposite polarities.

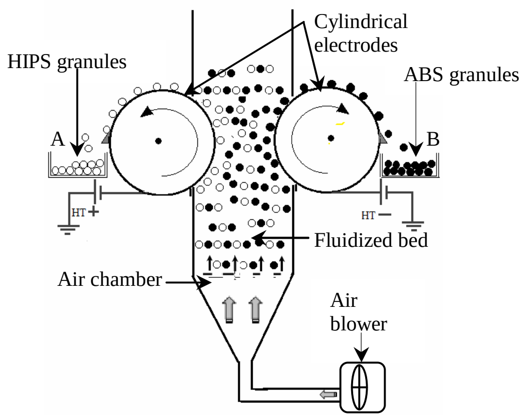


Fig. 1, Schematic representation of the new tribo-aero-electrostatic separation process.

The problem is that the charge acquired by the granules in these devices is not homogeneous. Some carry enough charge to be separated in an intense electric field, while others exit the tribocharging device with a less satisfactory charge level. The charge level can certainly be improved by increasing the duration of the tribocharging process, but this would diminish the hourly output of the installation. For a given particle residence time in the tribocharging device, the acquired charge can significantly vary with the ambient humidity, and with the surface state of the granules.

A recently patented installation avoids these drawbacks, by the simultaneous usage of the triboelectric effect, the Coulomb force and the electric image force [21-25]. Thus, the triboelectric effect provides the homogeneity of the electric charge acquired by the granules in a fluidized bed generated by a vertical air flow. The granules move in the electric field generated between two conveyor-belt-type high-voltage electrodes. Under the action of the Coulomb force, the granules are driven to the surface of these electrodes, to which they stay pinned by the electric image force. Then the electrodes convey them to the product collectors.

The aim of the present paper is to investigate the efficiency of a new design, in which the conveyor-belt electrodes are replaced by two metallic rolls (Fig. 1). The modified process is modeled using the experimental design methodology [26].

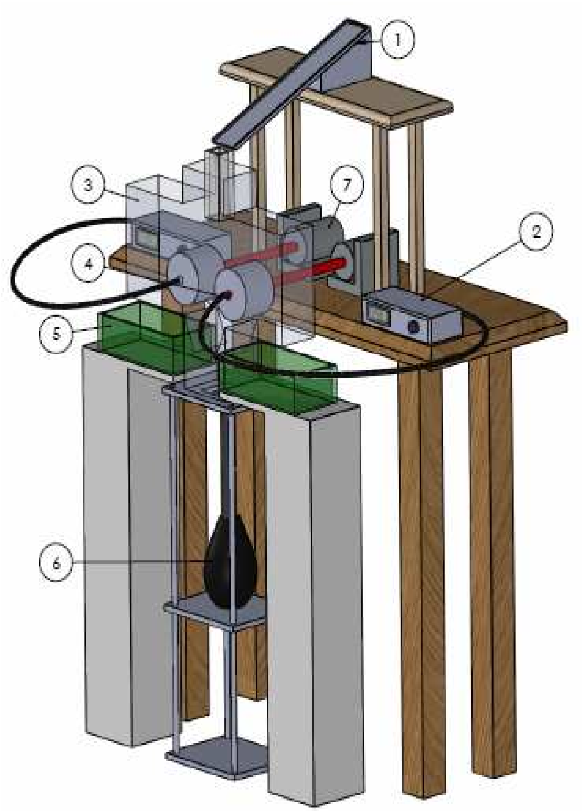


Fig. 2. Schematic representation of the modified tribo-aero-electrostatic separator; 1: Vibratory feeder; 2: DC high-voltage supplies; 3: Separation chamber; 4: Roll-type electrode; 5: Collecting box; 6: Blower, 7: Motor.

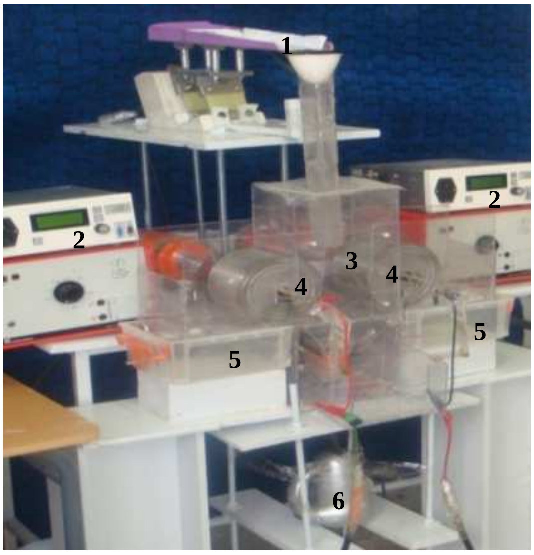


Fig. 3. Photograph of the laboratory tribo-aero-electrostatic separator 1: Vibratory feeder; 2: DC high-voltage supply; 3: Separation chamber; 4: Roll electrodes; 5: Collecting boxes; 6: Blower.

Fig. 4. Aspect and size of the granular materials (white: ABS; grey: HIPS).

II. Experimental Set-Up

A schematic representation of the modified tribo-aero-electrostatic separator built at the University Djillali Liabes of Sidi-Bel-Abbes, Algeria, can be examined in Fig. 2. An adjustable vibratory feed 1 introduces the granular material in the fluidized bed generated inside the separation chamber 3, which has a volume of 9620 cm^3 and transparent PMMA walls, to facilitate the visualization of the process. The fluidization air is provided at variable-speed by a blower 6.

The electric field is generated between the two rotating roll electrodes 4 (diameter: 11 cm; length: 7.5 cm) that are distanced at 7 cm and located in the separation chamber. They are energized from two high voltage power supplies 2 of opposite polarities, and entrained at variable speed by the DC motors 7. The products of the separation are collected in two boxes 5 placed on either side of the separation chamber.

III. Materials and Method

The two classes of plastics employed for the present study, ABS and HIPS are commonly found in the granular mixtures processed by electrostatic separation. They originated from information technology wastes processed by an industrial scrap recycler, APR2, Bonnières-sur-Seine, France.

The granular materials were obtained by crushing out-of-use computer housings and other electronic equipment. The granule size for both materials is less than 2 mm (Fig. 3). The experiments were carried out on samples consisting of 75 g ABS and 75 g HIPS granules.

According to the experimental design methodology, a two-step procedure was adopted:

Step 1): Define the domain of variation of the control factors: duration T of the process (T_{min}, T_{max}), high-voltage U applied to the roll electrodes (U_{min}, U_{max}), and speed v of the fluidization air (v_{min}, v_{max}) by varying one factor at a time and keeping the others constant.

Experiment 1: vary the duration T between 0 min and 5 min at U = 18 kV and v = 6 m/s.

Experiment 2: vary the positive/negative high voltage U between ±14 kV and ±22 kV, at T = 4 min and v = 6 m/s.

Experiment 3: vary the air speed v between 4 m/s and 8 m/s at T = 4 min and U = 20 kV.

Step 2): Identify the optimum operation conditions (T_o, U_o, v_o) by using a composite experimental design (Table I). The levels −1 and +1 of the control variables are respectively the minimum and maximum limits established in Step 1).

The experimental design procedure enables the derivation of quadratic models of the responses y_{ABS}, y_{HIPS}, y_{Mid}, i.e. express the masses of the three collected products as functions of the control variables *U*, *T*, and *v*:

$$y = a_0 + a_1 U + a_2 T + a_3 \nu + a_{11} U^2 + a_{22} T^2 + a_{33} \nu + a_{12} U * T + a_{13} U * \nu + a_{23} T * \nu \quad (1)$$

For electrostatic separation processes under study, the objective was to minimize the middling fraction.

In order to obtain such quadratic models, the data of the composite factorial experimental design were analyzed with MODDE 5.0 software (Umetrics, Sweden) [27], 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 near unity.

After each experiment, the ABS and HIPS products collected in the two boxes and the middling product remained in the fluidized bed were weighed with an electronic scale (resolution: 0.1 g). All the tests were carried out on the same sample, at stable environmental conditions: 19–21°C, relative humidity 46–50%.

IV. RESULTS AND DISCUSSION

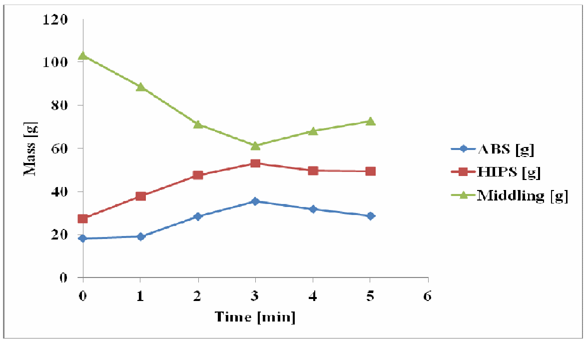
A. *Domain of Variation of the control Factors*

The masses of HIPS, ABS and middling recovered in the first three experiments are given in Fig. 5.

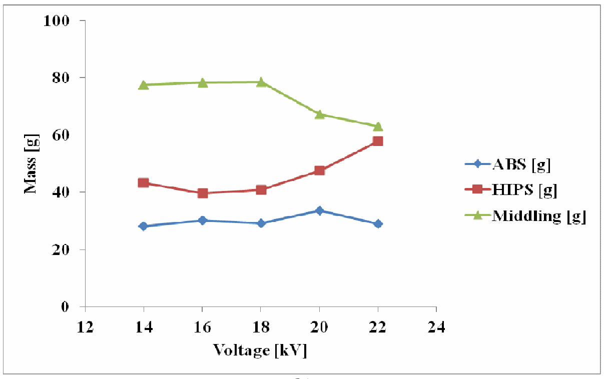
The graph in Fig. 5.a points out that, in the conditions of the experiment #1, the mass of middling decreases significantly for $T > 2$ min, while the quantities of HIPS and ABS increase, to attain a saturation value. Increasing the duration of the process beyond $T = 4$ min would be useless, as no more granules can get out of the fluidized bed (the lower limit of the fluidization mass is attained). Consequently, the domain of variation of *T* was defined as follows: $T_{min} = 2$ min and $T_{max} = 4$ min.

In the conditions of experiment #2 (Fig. 5.b), the results of separation are unsatisfactory for $U < 17$ kV. Thus, the lower limit of the high voltage was established as: $U_{min} = 18$ kV. The upper limit $U_{max} = 22$ kV was imposed by the occurrence of corona discharges from the electrode edges, a phenomena which alters the quality of the separation.

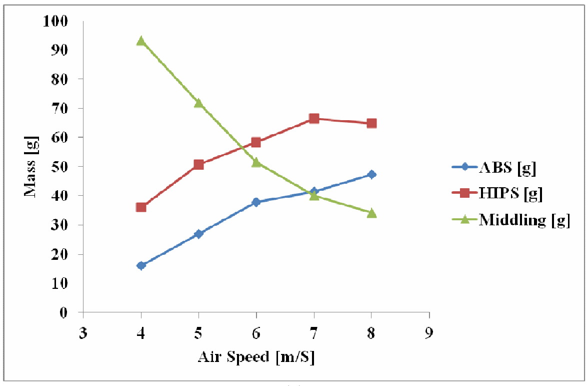
The experiment #3 (Fig. 5.b) shows that the air speed *v* is the most influential factor. The masses of the collected ABS and HIPS products increase quite steeply with *v*, to attain respectively the maximum values of 45.2 g and 60.8 g, at the air speed 8 m/s, for which the mass of the middling was 38.2 g. The domain of variation of the air speed was defined as: $v_{min} = 6$ m/s and $v_{max} = 8$ m/s. For an air speed higher than 8 m/s, the fluidized bed does no longer operate properly.



(a)



(b)



(c)

Fig.5. Mass of the products obtained from 150 g samples of 50% ABS – 50% HIPS, as function of: (a) the duration *T*; (b) the applied voltage *U*; (c) the air speed *v*.

B. *Set Point Identification*

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* were obtained with MODDE 5.0 and after elimination of the non-significant coefficients could be expressed as follows:

$$y_{ABS} = 5.02 + 9.7v - 6.63U^2 - 6.93T^2 - 1.1Uv \quad (4)$$

$$y_{HIPS} = 42.93 + 0.98T + 3.98v + 4.47U^2 + 7.23T^2 + 1.4UT + 2.78Tv \quad (5)$$

$$y_{Mid} = 58.19 - 13.66v + 1.78U^2 - 1.68v^2 - 1.17UT - 3.1Tv + 3.83Uv \quad (6)$$

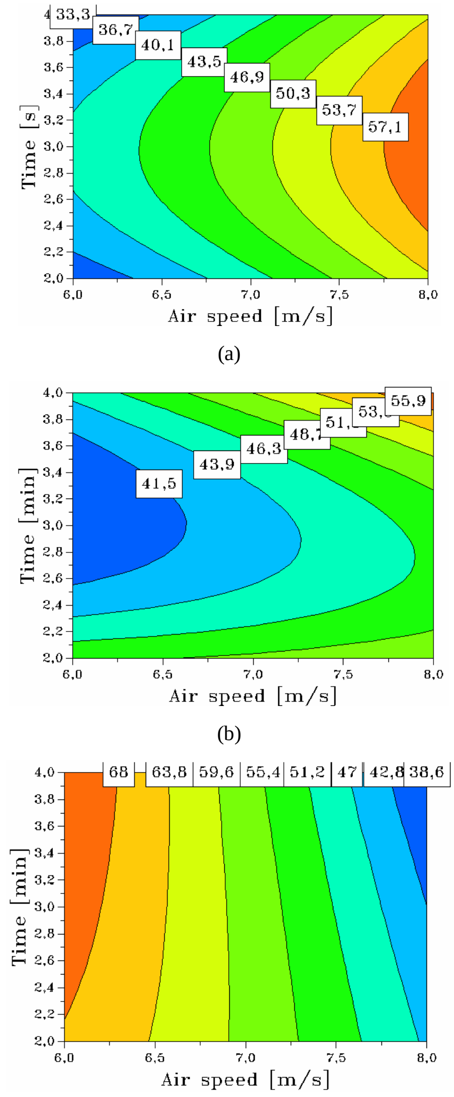
TABLE I.
MASSES OF THE PRODUCTS OBTAINED FROM A 75 G HIPS + 75 G ABS GRANULAR MIXTURE, USING A COMPOSITE FACTORIAL EXPERIMENTAL DESIGN

T [min]	*U* [kV]	ν [m/s]	ABS [g]	HIPS [g]	Mixt [g]
2	18	6	27.7	51.8	70.1
4	18	6	25.5	45.1	78.4
2	22	6	28.8	54,0	67,0
4	22	6	28.5	53.5	67.5
2	18	8	46.9	59.5	42.6
4	18	8	48.9	64.5	35.4
2	22	8	46.5	51.4	51.5
4	22	8	44.6	61.4	43.1
2	20	7	40.4	49.4	59.4
4	20	7	41.2	51.4	56.1
3	18	7	41.8	47.6	59.7
3	22	7	40.4	48.3	60.4
3	20	6	38.8	39.8	70.8
3	20	8	59.3	47.1	42.7
3	20	7	50.7	42.7	55.8
3	20	7	50.3	42.8	55.6
3	20	7	51.6	42.3	55.2

The two statistical criteria computed by MODDE 5.0 were excellent for all the models: the goodness of fit R^2 = 0.91, 0.981 and 0.961; the goodness of prediction Q^2 = 0.985, 0.968 and 0.941.The predicted mass of collected ABS, HIPS and middling are represented in Figs. 6 and 7.

The ABS granules get well charged and can be easily separated after a fluidization process of shorter duration than the HIPS. A longer charging process is favorable for the recovery of HIPS granules. For both classes of particles, the best results were obtained at higher speed of the fluidization air.

MODDE 5.0 offered also the possibility of identifying the optimal operation conditions (the set-point) of the process: T = 4 min, U = 18.2 kV and v = 8 m/s, for which the predicted masses of the three collected products were: y_{ABS}=49.35 g, y_{HIPS}=63.21 g and y_{Mid}=37.42 g. The masses collected in an experiment conducted for the above-listed values of T, U and v were: y_{ABS} = 49.7 g, y_{HIPS} = 60.1 g and y_{Mid} = 37.8 g, in very good agreement with the predictions



(c)

Fig. 6. MODDE 5.0 – computed equal response contours of ABS (a), HIPS (b) and Middling (c) masses for U = 18 kV.

V. CONCLUSIONS

(1) The new tribo-aero-electrostatic separator has proven its efficiency in the processing of granular plastic mixtures. such as those originating from WEEEs. The simultaneous charging and separation of the granules in a fluidized bed in the presence of an intense electric field is a complex physical phenomenon, depending on a multitude of factors: the speed of the fluidizing air, the high-voltage applied to the electrode system, and the duration of the process.

(2) The experimental design methodology may be useful in the modelling and optimization of the separation process for any similar application in the WEEE recycling industry.

(3) The results of this laboratory are very encouraging. However, they have still to be confirmed on an industrial pilot installation.

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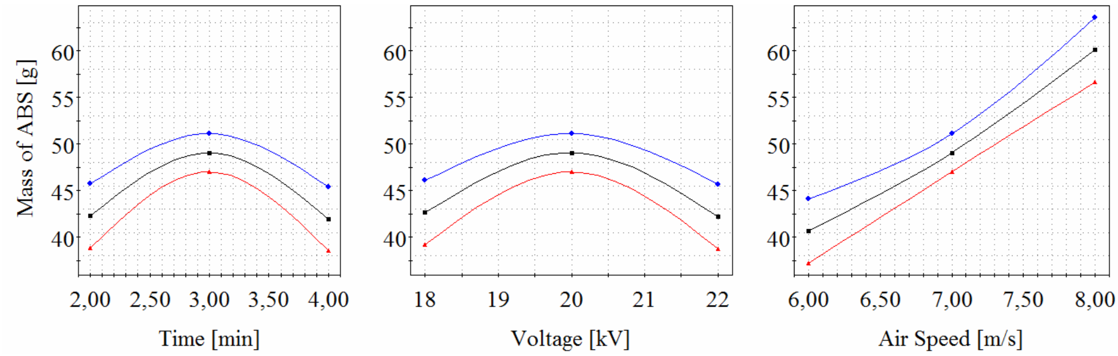
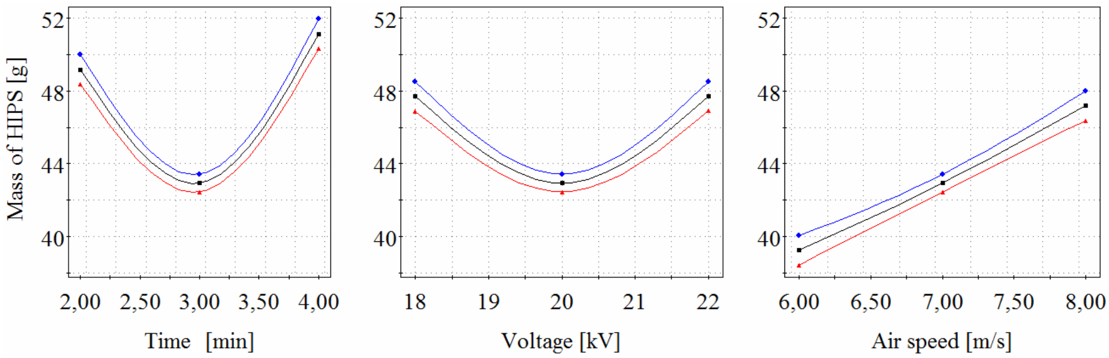


(a)



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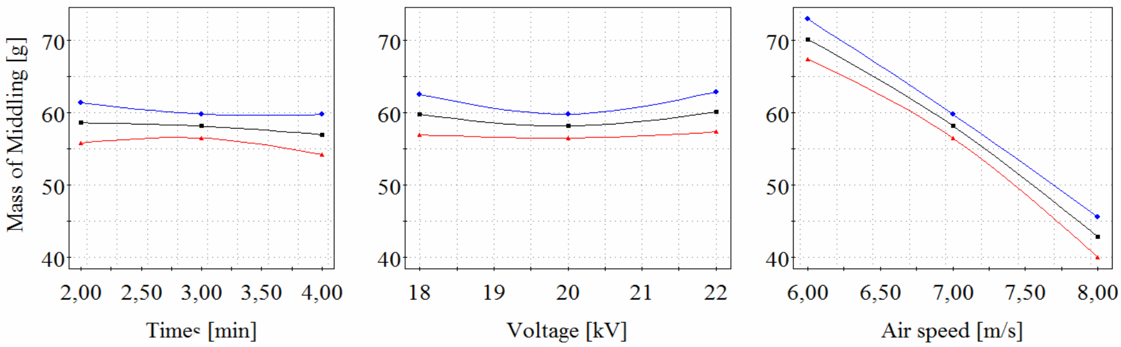

(c)

Fig. 7. MODDE-predicted masses of ABS (a) HIPS (b), and middling (c) as function of the duration T, the high-voltage U, and the air speed v. In each case, the other variables are maintained constant and equal to their central values T = 3 min, U = 20 kV. and v = 7 m/s. The upper and lower curve on each graph indicate the limits of the 95% confidence level interval

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