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MODELLING AND OPTIMIZATION OF THE WASTE MICRONIZED PLASTICS RECOVERY BY TRIBOELECTROSTATIC SEPARATOR

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Abstract

Triboelectrostatic separation of millimeter-size particles is widely used in the recycling industry of plastics. However, the separation of micronized particles needs still improvement due to the aerodynamic forces of such small particles. This paper is aimed to carry out an experimental investigation of a triboelectrostatic separation process based on a pair of rotating disks supplied by two high-voltage DC supplies of opposite polarities. The granular samples used in this paper are composed of micronized white pure virgin PolyVinyl Chloride particles (WPVC) and gray PolyVinyl Chloride particles (GPVC) of average size 50 μm. Moreover, the methodology of experimental designs was used for the experimental modelling and optimization of the separation process. It was deduced that the separation recovery is efficient and depends on several factors: the high-voltage level, the rotating speed of the disks, the fluidization rate and inter-electrodes spacing. The results obtained showed that the applied voltage remains the most significant factor in the separation process. The best separation performance was obtained for an applied voltage of 20 kV and a disk rotation speed of 100 rpm.

Key words: fluidized bed, plastic particles, tribo-electrostatic separation, recycling

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1. Introduction

The rapid growth of the recycling industry, stimulated by increasingly strict regulations concerning environmental protection, is accompanied by an increase in research and development efforts in this area (Singh and Pant, 2018). The separation of solid granular mixtures using electrical forces (De Gisi et al., 2020; Iuga et al., 2016; Tilmatine et al., 2009; Wu et al., 2013), is a promising technology for electrical and electronic treating waste equipment (Bilici et al., 2011; Calin et al., 2008; Jia et al., 2008; Zelmat et al., 2013a, 2013b).

In the last few years, various devices using the triboelectric effect have been designed and constructed as a means of charging granular for separation into an electric field, according to the electrode polarity and the acquired charge polarity (Grosshans and Papalexandris, 2016; Kolehmainen et al., 2016; Miloudi et al., 2011; Shin et al., 2015; Sow et al., 2013).

Despite research efforts aimed at the realization and optimization of various types of electrostatic precipitators, the industrial application of such technology remains problematic for micronized particles (Benabboun et al., 2014; Zelmat et al., 2017). High yields of separation are obtained for granular mixtures of millimetres size (Rezoug et al., 2015), but for micrometre-sized particles, the separation processes are less efficient due to the aerodynamic forces that affect their trajectories.

Previous detailed experimental results related to the same aero-tribo-electrostatic separation process have been reported by the Electrostatics research

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group of Angouleme, France. Several factors were studied by the authors to analyze their influence on the performance of the separation process. Mekhalef et al. (2018) analyzed the effect of the applied voltage, the mass of the total mass of the granular product introduced in the fluidized bed, the fluidization rate and the rotation speed of the disk electrodes. Moreover, the size of the particles to be separated and the optimal design for a possible application in the recycling industry were thoroughly studied (Achouri et al., 2019; Zeghloul et al., 2017).

This paper aims to present an experimental optimization of a new tribo-electrostatic separator that was previously developed and analysed by almost the same authors (Tilmatine et al., 2014). This type of electrostatic separator has already been studied, the main objective of the present paper is to establish an experimental model and use it for optimization analysis of the process. The installation consists of two metal disks rotating at a given speed, connected to two high-voltage DC power supplies of opposite polarity. These two rotating electrodes are immersed in a fluidised bed which contains the mixture of particles to be separated. The peculiarity of this device is that tribo- electric charging and separation operations occur simultaneously in the same area and that two rotating disks are used instead of two fixed vertical electrodes as is the case with the conventional separator.

2. Material and methods

The tribo-electrostatic separator is shown in Fig. 1. The mixture of particles is deposited on an insulating sieve inside the separation chamber measuring 21 cm x 22.5 cm x 18 cm, made with transparent PMMA (plexiglass) walls. The air is injected by a blower with a power of 750 W and variable flow rate by means of a variable frequency drive. The fluidized bed schematically shown in Fig. 3 is characterized by a cross-section of 21 cm x 22.5 cm and a height of 10 cm from the PVC screen on which the product is deposited. This sieve, distributing the air uniformly in the fluidised bed, is made of 0.1 mm average mesh size. The initial mass of product in the fluidized bed was 600 g. The electrostatic effects of triboelectric charging within the fluidized bed are due to particle-particle and particle-wall collisions, which result in the triboelectrification of the mixture of micronized materials.

The electric field is generated between the two rotating electrodes. These steel discs of 22 cm in diameter and 4 mm thickness are separated by a variable interval of 4 to 12 cm and immersed 3 cm into the fluidized bed (Fig. 1). The disks are powered by two high voltage generators of opposite polarity and driven at variable speed by a direct current motor.

Aggregation is a common problem for this particle size; however, fluidization in the presence of the electric field prevents this phenomenon. The particles are attracted by electrodes of opposite polarity and collected in two compartments located on either side of the separation chamber.

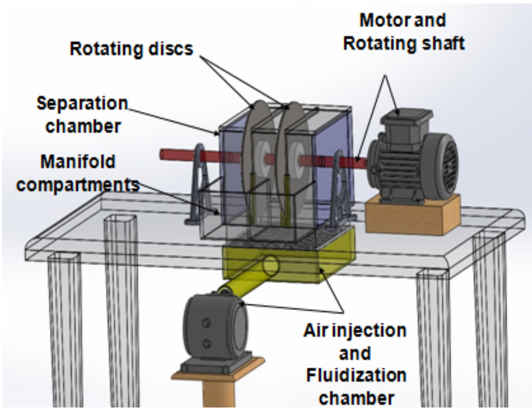


Fig. 1. Representation of the tribo-electrostatic separator

The powder product used for this study consists of two different types of PVC supplied by an industrial manufacturer of PVC plastic pipes, CHIALI Group, Sidi Bel-Abbes, Algeria. "White PVC" (WPVC) is a pure virgin polymer, while "grey PVC" (GPVC) contains a small percentage of carbon. The surface properties are modified and therefore the two types of PVC are charged differently by the triboelectric effect. The powdered material was obtained by grinding the PVC pipes to be recycled. A fine-mesh sieve was used to recover the finest particles with an average size of 50 µm (Fig. 2). The experiments were carried out on samples with a total mass of 600 g, consisting of 50% WPVC and 50% GPVC.

(a) (b) (c)

Fig. 2. Aspect of the particles used in the experiments: (a) White PVC, (b) Mixed PVC and (c) Grey PVC

In each experiment, the blower is switched on and the materials are pre-charged into the fluidized bed. Then the rotation of the rotating discs is started, and the separation process starts as soon as the high-voltage power supply is switched on. The process is stopped as soon as the purity of the separated products starts to decrease. This degradation of operation is observed when the product remaining in the fluidized bed becomes less than about 100 g. The mass of the product collected in each collection compartment was weighed using a 0.1 g precision electronic balance. For each experiment two tests were carried out and the mean value was used to draw the curves.

The experimental study was carried out considering four factors: the inter-electrode distance d (cm), the positive/negative high voltage V (kV), the air injection rate F (L/min) and the disk rotation speed n (rpm). The tests were carried out at ambient temperature (19°C to 24°C), with relative air humidity ranging from 40 to 60%.

2.1. Experimental designs methodology

Methodology of the experimental designs was often applied for purely experimental work which required having some information on the influence of each input factor and their interactions on the response or the output to be studied (Behbahani et al., 2013; Bezerra et al., 2008).

In this paper, the Experimental designs methodology is also using for optimization of the separation process. In this reason, the Composite Centred Faces design (CCF), which gives quadratic models was applied.

The mathematic model for CCF design can be write by following equation (Eq. 1):

$$y = f(u_i) = c_0 + \sum c_i u_i + \sum c_{ij} u_i u_j + \sum c_{ii} u_i^2 \qquad (1)$$

With: u_i *(i = 1, ..., k)*

In the experimental design method, it is important to define the reduced cantered values while knowing the step of variation Δu_i and the central value u_{i0} of each input factor i as following (Eq. 2):

$$x_i = (u_i - u_{i0}) / \Delta u_i \qquad (2)$$

With these new variables, the output function becomes (Eq. 3):

$$y = f(x_i) = a_0 + \sum a_i x_i + \sum a_{ij} x_i x_j + \sum a_{ii} x_i^2 \qquad (3)$$

The coefficients can be calculated or estimated by a data-processing program, in such a way to have a minimum variance between the predictive mathematical model and the experimental results.

When you want to understand how a process or a machine works, you have to go through experimentation. For this, setting up a design of experiments is the best solution and it is better to be guided by a design of experiment software.

MODDE 5.0, ultra-simple design of experiment software, its automatic interface guides you to quickly set up a design of experiments without special knowledge.

MODDE 5.0 allows you to go much further in the analysis of results by calculates the coefficients of the mathematical model and identifies best adjustments of the factors for optimizing the process. Before this, MODDE 5.0 need to calculate two significant statistical criteria which make it possible to validate or not the mathematical model, symbolized by R^2 and Q^2 which are varied between 0 and 1, where 1 indicates a perfect model and 0 no model at all and preferably not separated by more than 0.2-0.3.

3. Results and discussion

The aim of these first experiments was to determine the range of variation for each factor, in preparation for a face-centred composite factorial design, which should enable the modelling and optimization of the separation process using MODDE 5.0 software (Umetrics AB, MODDE 5.0).

In this study, classical "one-factor-at-a-time" experiments were carried out to identify the domain of variation of the four following factors:

1. Applied High voltage level *V* (kV);
2. Inter-électrodes distance *d* (cm);
3. Rotational speed of the electrodes *n* (rpm).
4. Fluidization air flow rate *F* (L/min)

"One factor at a time" experiments consist of studying the variation of each factor while keeping the rest of the other factors at constant values (Figs. 3-6).

We see that the recovery rate of two PVC products increases with the applied voltage up to 16 kV, and decreases for the higher values of the field (Fig. 3).

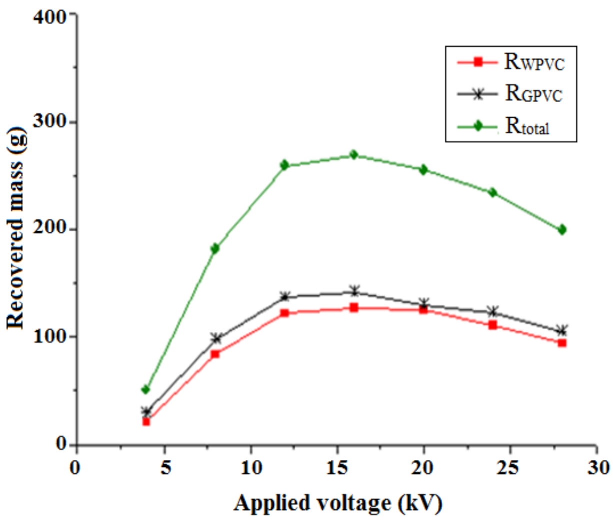


Fig. 3. Evolution of recovery variation rates according the applied voltage (d =4 cm, F = 21 L/min, n = 120 rpm)

In this case, the electrical force becomes greater and a large amount of product is quickly collected on both discs, which eventually covers the electrodes completely. As a result, the other oppositely charged product will attach to this electrode causing the separation efficiency to decrease. So, based on these results we have chosen U_{min} = 12 kV and U_{max} = 20 kV for the limits of the voltage variation interval.

The recovery mass decrease by increasing the distance between the disks, that is explained by the electric force decrease which is responsible for collection of the mixture at the disks (Fig. 4). So, based on these results, we have chosen d_{min} = 4 cm and d_{max} = 8 cm for the limits of the distance variation interval.

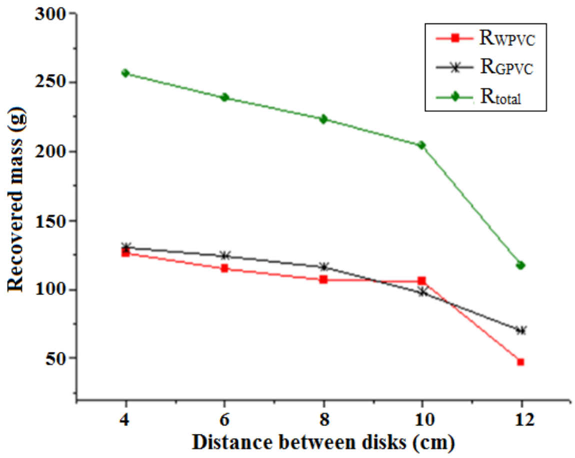


Fig. 4. Evolution of recovery variation rates according the distance inter-disks (V =12 kV, F = 21 L/min, n = 120 rpm)

In addition to the electrical imaging force that causes the particles to attach to the disk, there is another mechanical force to consider: the centrifugal force, which is proportional to the rotational speed of disks n. As the centrifugal force increases, it causes the particles to detach and the separation efficiency to decrease (Fig. 5). On the other hand, for reduced values of speed n, the granules have enough time to rapidly cover the entire disc surface causing the attachment of opposite electrical charge particles, thus decreasing the recovery rate. According to the results shown in Fig. 5, the speed variation range was chosen as follows: n_{min} = 60 rpm and n_{max} = 100 rpm.

The variation in recovery as a function of air flow is shown in Fig. 6, which shows that it is not necessary to increase the fluidization rate too much. Indeed, when the air flow rate increases, the particles acquire a higher triboelectric charge and the phenomenon of attraction between the two types of PVC on the disc will cause a decrease in separation efficiency.

Therefore, when the disc is completely covered with one type of PVC causing the formation of a layer about 1 mm thickness, the other type of PVC will begin to attach to it. According to our case study, the optimal value for air injection is approximately 24 L/min. The limits of the variation range for this factor are F_{max} = 21 L/min and F_{min} = 26 L/min.

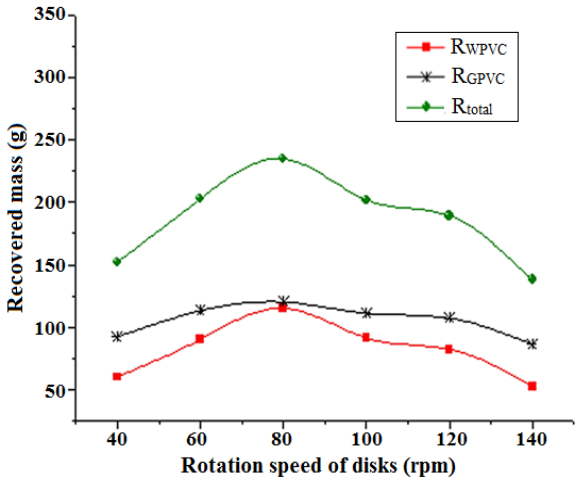


Fig. 5. Evolution of recovery variation rates according the speed of disks (V= 12 kV, d =4 cm, F = 21 L/min)

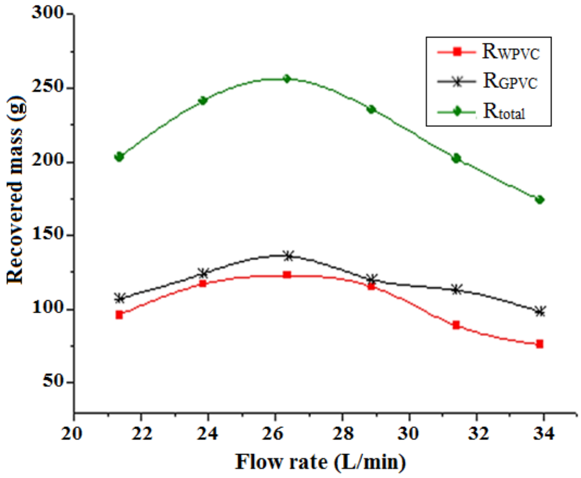


Fig. 6. Evolution of recovery variation rates according the flow rate (V= 12 kV, d =4 cm, n = 80 rpm)

3.1. Composite Centred Faces design (CCF)

The study of the effects of factors and their iterations is one of the important characteristics to study in order to determine the performance of the separation process. Their analysis is a key factor for a good optimization of the powder separation.

The CCF Design of Experiment is applied in this study to evaluate the effects of each factor on the responses defined by domain of variation.

A central CCF design was then carried out for identifying the set point (V_0, d_0, n_0 and F_0), the two levels "max" and "min" are the limits established in previous section for each of the four input variables (V_{min}, V_{max}), (d_{min}, d_{max}), (n_{min}, n_{max}) and (F_{min}, F_{max}) the central point (V_c, d_c, n_c and F_c) being calculated as follows Eqs. (4-7):

$$V_C = (V_{\min} + V_{\max})/2 = (12+20)/2 = 16kV \quad (4)$$

$$d_C = (d_{\min} + d_{\max})/2 = (4+8)/2 = 6\ cm \quad (5)$$

$$n_C = (n_{\min} + n_{\max})/2 = (60+100) = 80\ rpm \quad (6)$$

$$F_C = (F_{\min} + F_{\max})/2 = (21+26) = 23.5 l/\min \quad (7)$$

The results of the face-centred composite design are presented in Table 1, considering the total mass recovered from the two *R_{total}* electrodes as the response of the process to be modelled. For the analysis of the experimental data, a specific software dedicated to experimental designs was used to make the various statistical calculations (Umetrics AB, MODDE 5.0). Once the results of the CCF design are introduced, the software validates or not the proposed mathematical model by checking two statistical criteria R^2 (quality of the regression) and Q^2 (quality of the prediction) which must be as close as possible to the unit. Then, the criteria (R^2 = 0.988, Q^2 = 0.936), (R^2 = 0.916, Q^2 = 0.768) and (R^2 = 0.975, Q^2 = 0.911) for R_{WPVC}, R_{GPVC} and R_{total}PVC respectively are close to unity, therefore the model is valid.

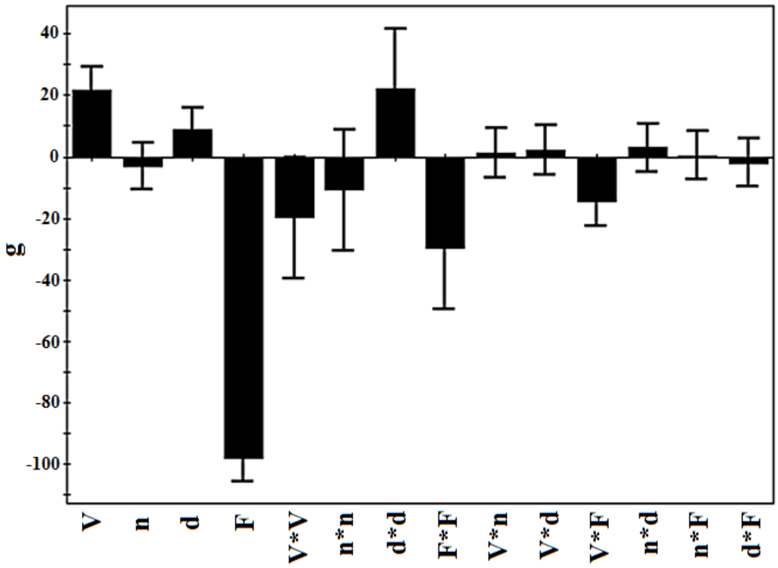
The plots of the coefficients given by MODDE.5.0 software represent the level of the influence of each factor on the mass recovered of white PVC, gray PVC and total PVC respectively (Figs. 7a-c). The graphs of Fig. 7 represent the plotted coefficients of the mathematical models for the three responses considered in the paper. When the standard variation of a factor I pass by the zero level, thus the factor I is considered as a non-significant factor. Higher values of the coefficients correspond to a greater influence on the response. A significant coefficient is a term with a large distance from y=0 and an uncertainty level that does not extend beyond y=0. On the other hand, a non-significant coefficient is close to the line y=0 and whose level of uncertainty crosses y=0. A positive number indicates a positive influence on the response while a negative number indicates a decreasing effect on the response. To match an accurate model, insignificant model coefficients should be removed.

Therefore, according to the plotted diagrams, all interactions between the four factors are non-significant. On the other hand, we notice that the factors voltage *V* and frequency *f* are more significant on the recovery rates in comparison with the two other factors, i.e. the rotation speed *n* and the inter-electrodes distance *d*.

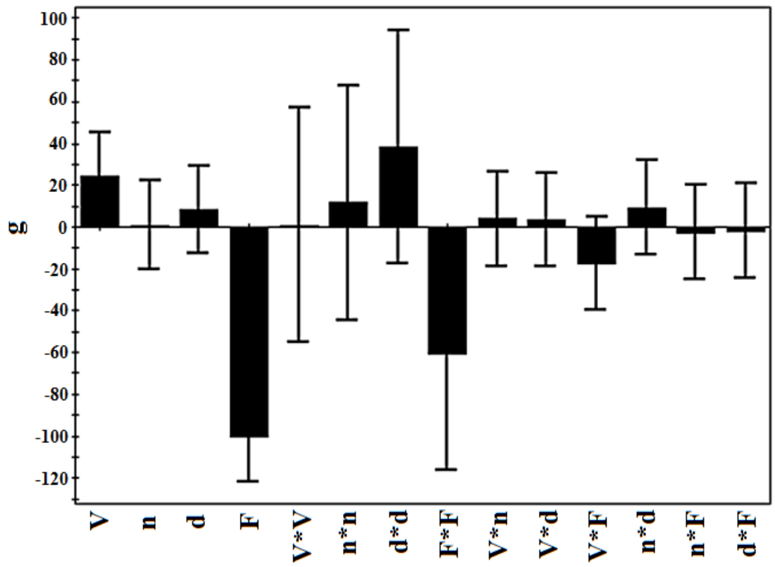
According to this model, the applied voltage and the flow rate of the injected air were the most important factors on the mass recovered. The increase of applied voltage leads to increase of electrical force and then increasing of recovered masses. However, the increase of flow rate has the opposite effect on recovered masses.

Table. 1. Results of recuperation white, grey and total PVC experience extract according to variation in treatment values

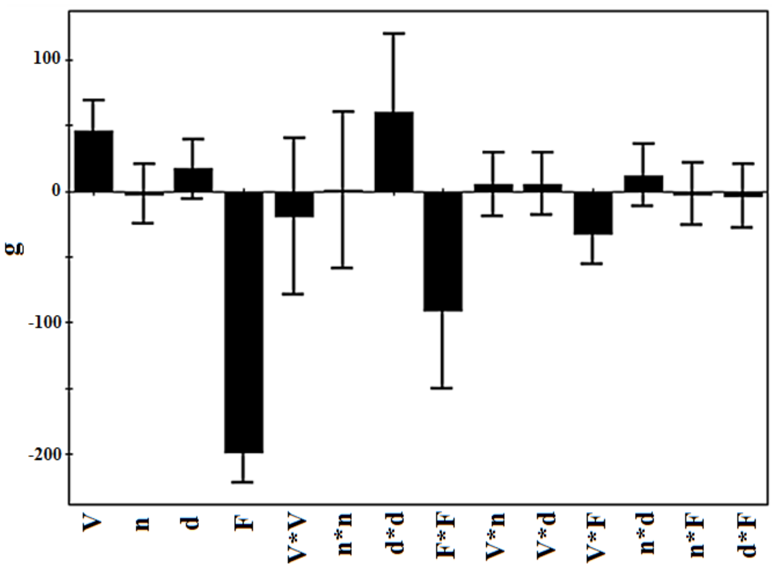
Exp No	*Applied Voltage(kV)*	*Distance(cm)*	*Rotation Speed(rpm)*	*Flow rate (L/min)*	*R_{WPVC}(g)*	*R_{GPVC}(g)*	*R_{Total}(g)*
1	12	4	100	21	178	193	371
2	20	4	100	21	233	260	493
3	12	8	60	21	145	153	298
4	20	8	60	21	230	243	473
5	12	8	100	21	177	173	350
6	20	8	100	21	252	243	495
7	12	4	60	26	194	209	403
8	20	4	60	26	256	309	565
9	12	4	100	26	6	6	12
10	20	4	100	26	7	6	13
11	12	8	60	26	6	7	13
12	20	8	60	26	7	12	19
13	12	8	100	26	15	12	27
14	20	8	100	26	34	33	67
15	12	6	80	23.5	9	9	18
16	20	6	80	23.5	30	33	63
17	16	6	60	23.5	88	108	196
18	16	6	100	23.5	158	170	328
19	16	4	80	23.5	148	165	313
20	16	8	80	23.5	116	134	250
21	16	6	80	21	165	171	336
22	16	6	80	26	165	182	347
23	16	6	80	23.5	221	149	370
24	16	6	80	23.5	5	6	11
25	16	6	80	23.5	162	161	323
26	12	4	100	21	159	15	174
27	20	4	100	21	159	15	174



(a)



(b)



(c)

Fig. 7. Diagram of the coefficients of the mathematical model: (a) R_{WPVC}, (b) R_{GPVC} and (c) R_{total}

The interaction between the voltage *V* and air flow rate *F* is significant in comparison with the other factors because they are directly related to the attraction force and the electric charge levels, respectively. However, the interaction effect between these two factors is negative; when both factors get simultaneously high values, the rotating disks become quickly covered by a great amount of the particles, causing the repulsion of the other particles of same charge polarity and thus causing the decrease of the recovery rate.

The mathematical models for white, grey and total recovered mass of PVC, respectively, proposed by MODDE.05 are Eqs. (8-10):

$$RWPVC = 148.91 + 21.61V^{*} + 8.61d^{*} - 98.16F^{*} + 22.12n^{*2} - 29.87F^{*2} - 14.68V^{*}F^{*} \quad (8)$$

$$RGPVC = 129.45 + 24.38V^{*} - 100.44F^{*} - 60.41F^{*} \quad (9)$$

$$RtotalPVC = 278.37 + 46\,V^{*} - 198.61F^{*} + 60.61d^{*2} - 90.38F^{*2} - 32V^{*}F^{*} \quad (10)$$

The data processing as well as the determination of mathematical model, resulting from the designs of experiments, requires the use of reduced values of factors, designated by “coded variables” (*V**, *d**, *n** and *F**), in place of “real variables” (*V*, *d*, *n* and *F*). These coded variables can be calculated by dividing the real factor value over the centred value of the same factors previously defined.

On the other hand, according to this model, the optimum of the process (i.e., the greatest amount of R_{WPVC}, R_{GPVC} and R_{total}PVC) should be obtained for applied voltage V_0= 20 kV, distance inter-disks d_0 = 8 cm, rotation speed n_0 = 100 rpm and flow rate F_0= 21 L/min (Fig. 8).

The satisfactory results obtained in this study show that the application of a new process for the separation and recycling of plastics from electronic and electrical waste is possible. The main advantage of the rotating disks separator is that the tribocharging mechanism of the particles and the separation occur simultaneously in the same area.

4. Conclusions

A tribo-electrostatic separator using two opposite high-voltage rotating disks was used for the separation of micronized plastic particles. The device was experimentally investigated by analyzing the effect of several factors, such as the applied high-voltage level *V* (kV), the rotation speed of the disks *n* (rev/min), the flow rate of injection air *F* (L/min) and the inter-electrodes spacing *d* (cm). Moreover, an experimental modelling and optimization of the separation process was carried out by using the design of experiments methodology.

The mixtures of µm-size plastic particles were successfully separated, with high levels of recovery and purity. Two important difficulties of the present study should be highlighted. First, it’s hard to determine with precision the purity of the separated products. Actually, since they are µm-size particles, it’s practically impossible to estimate manually the purity of the products. The purity was determined visually, the quality of the separated products is easily identified when the colour becomes changing.

Secondly, when the mixture is not 50%/50%, some preliminary experiments not included in the paper, showed that indeed the minority product is more charged and thus is better separated. On the other hand, the majority product gets a lower charge, due to the little number of collisions with the minority product, and thus is not well separated.

	Factor	Role
1	Applied voltage	Free
2	Rotation speed	Free
3	Distance inetr-disks	Free
4	Flow rate	Free

	Response	Criteria	Weight	Min	Target	Max
1	Recupeartion of white PVC	Maximize	1	245.059	271.499	
2	recuperation of grey PVC	Maximize	1	276.096	308.476	
3	Recuperation tolal	Maximize	1	522.446	578.68	

Iteration: 5005 Iteration slider:

	1	2	3	4	5	6	7
	Applied voltage	Rotation speed	Distance inetr-disks	Flow rate	Recupeartion of white PVC	recuperation of grey PVC	Recuperation tolal
1	19.9774	99.678	7.9972	21.0141	258.224	291.217	549.441
2	18.1328	83.9997	4.0587	21	238.819	216.251	455.069
3	20	69.4491	4	21	242.765	241.196	483.959
4	19,985	84	8	21.0015	268.168	267.736	535.902
5	19.9989	97.0264	8	21.0613	259.815	286.577	546.391
6	20	64	4	21	240.258	245.876	486.133
7	19.9999	99.9971	7.9994	21.0006	258.252	292.249	550.5
8	20	100	8	21	258.279	292.286	550.563

Fig. 8. Subroutine of MODDE.05 representing the set point

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