

Robust Design of Electrostatic Separation Processes

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Abstract—The aim of this paper is to analyze the robustness of the electrostatic separation process control. The objective was to reduce variation in the process outcome by finding operating conditions (high-voltage level, roll speed), under which uncontrollable variation in the noise factors (granule size, composition of the material to be separated) has minimal impact on the quantity (and the quality) of the recovered products. The experiments were carried out on a laboratory roll-type electrostatic separator, provided with a corona electrode and a tubular electrode, both connected to a dc high-voltage supply. The samples of processed material were prepared from genuine chopped electric wire wastes (granule size >1 mm and <5 mm) containing various proportions of copper and PVC. The design and noise factors were combined into one single experimental design, based on Taguchi's approach, and a regression model of the process was fitted. The impact of the noise factors could be estimated, as well as the interactions between the design and noise factors. The conditions of industry application of Taguchi's methodology are discussed, as well as the possibility of adapting it to other electrostatic processes.

Index Terms—Design of experiments, electrostatic separation, robust process design, Taguchi's experimental design.

I. INTRODUCTION

SEPARATION of mixed granular solids under the action of electric forces [1]–[4] is a mature field of applied electrostatics. The progress achieved during the last 20 years can be perceived by reading the abundant technical literature published in this field, including several well-documented reviews [5], [6].

However, the innovations in the design of the electrode systems [7], the various recommendations produced by the numerical and/or experimental studies of particle charging mechanisms [8]–[10], and the conclusions of particle trajectories calculations [11] induced only marginal changes in the “classical” technologies and have a limited impact on the quality, reliability, or economy of electrostatic processes applications. Roll-type separators remain the most widely used, because of

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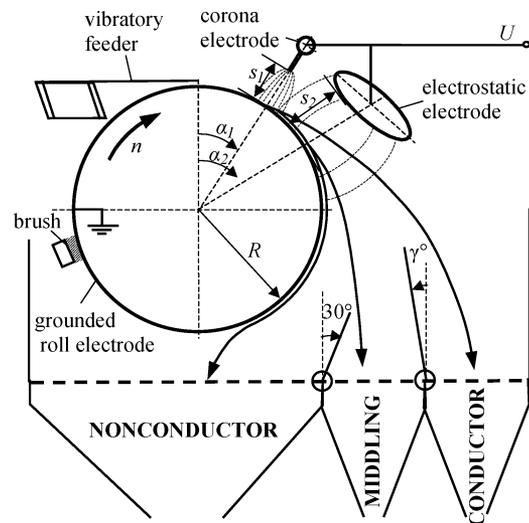


Fig. 1. Control variables of an electrostatic separation process: high-voltage level U roll speed n ; angular ($\alpha_1 = 30^\circ$) and radial ($s_1 = 40$ mm) position of the corona electrode; angular ($\alpha_2 = 70^\circ$) and radial ($s_2 = 70$ mm) position of the electrostatic electrode; angular position ($\gamma = -4^\circ$) of the splitter.

the possibility of controlling the output of the process by regulating several input variables, such as the high-voltage level, the roll speed, or the position of the corona and electrostatic electrodes (Fig. 1).

Taguchi's methodology of experimental design [12]–[18] belongs to a class of approaches that attempt to produce significant overall improvement of the performance attained by such processes. The conceptual framework is based on the idea that the control factors should be optimized for the attainment of a specified target value and the elimination of variation. According to Taguchi, variability in the target value will increase the “loss to society.”

A robust process is one that is insensitive to any source of naturally occurring, difficult to control variations in materials, environmental conditions, or operator conduct. All these are commonly referred to as “noise,” and the aim of the present paper is to analyze how experimental design techniques could be employed for limiting the “loss to society” due to a specific group of such factors: those related to the characteristics of the materials that are separated.

II. PROBLEM FORMULATION

The study was carried out on a typical electrostatic separation process: the selective sorting of copper and plastics from chopped electric wire wastes [7], [19], [20]. The “robust design” of such a process consists of finding the conditions where, simultaneously, the responses have values close to the target and low variability. Taguchi's methodology adopted in this work distinguishes between easy-to-control “design factors,”

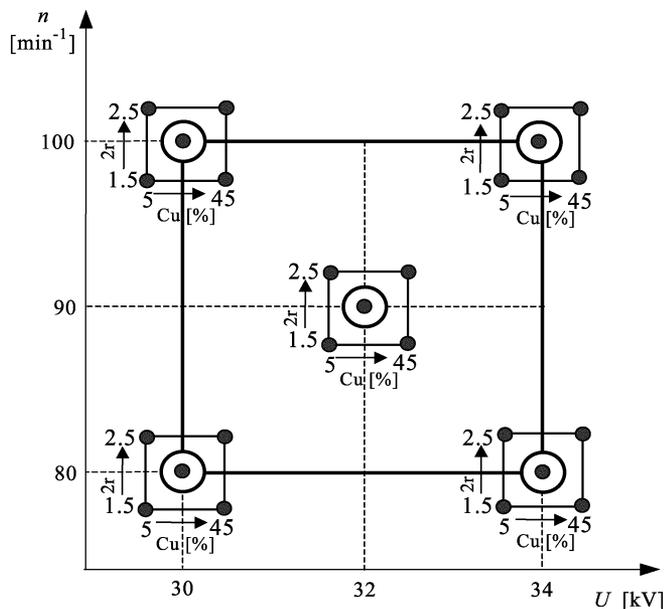


Fig. 2. The “design factors,” voltage and roll speed, and the “noise factors,” granule size and copper content, represented as, respectively, inner and outer arrays of an experimental design.

and hard-to-control “noise factors.” The former essentially affect the mean output of the process. The latter may or may not affect the mean response of the process and the spread of the response values around that mean. The analysis of the experimental data should enable the identification of the factors which affect only the mean, only the spread around the mean, or both properties.

In order to facilitate the identification of the “robust design,” the authors followed Taguchi’s approach and arranged the design and noise factors as inner and outer orthogonal arrays (Fig. 2). The voltage U and roll speed n were used as design factors, and varied in a square inner array chosen in accordance with the recommendations of a previous study [21]: $U_{\min} = 30$ kV, $U_{\max} = 34$ kV, $n_{\min} = 80$ min⁻¹, $n_{\max} = 100$ min⁻¹.

The median granule diameter d and the copper content c were the two noise factors incorporated into the experimental design as a square outer array. They could be rigorously adjusted in this experiment, but are not controllable in the industrial process. Their respective limit values $r_{\min} = 1.5$ mm, $r_{\max} = 2.5$ mm, $c_{\min} = 5\%$, and $c_{\max} = 45\%$ were chosen from the data furnished by the supplier of the wire cable waste that was separated.

For each design point in the inner array, a square outer array is laid out. The number of experiments according to each inner and outer array is five, which makes $5 \times 5 = 25$ experiments necessary. Two additional experiments in the central design point were performed, in order to estimate the reproducibility of the response, which makes a total of $25 + 2 = 27$ separation tests.

The target of the experimental design is to maximize the recovery of high-grade conductor and nonconductor products, by minimizing the quantity of middling M . This criterion seems to be of little relevance for the industrial practice, where the middling fraction is recycled into the feed for re-separation, and the customer is primarily interested in having pure conductor (C)

TABLE I
SAMPLE DEFINITION

Copper content c [%]	Median granule size d [mm]		
	1.5	2	2.5
5	S11		S12
25		S00	
45	S21		S22

and nonconductor (NC) products. However, there are at least three sound arguments in favor of the choice made here.

- 1) The mass of middlings is a process variable that can be easily measured, either on- or off-line. Conversely, purity is a response the evaluation of which requires complex and time-consuming offline analysis of the products; it cannot, hence, be employed for implementing effective process control procedures.
- 2) The results of previous laboratory studies have shown that larger quantities of middlings are most often associated with lower grades of the C product and poor recovery of the insulating material in the NC product. This situation occurs when—under the action of the centrifugal forces—a significant percentage of the insulating particles detach earlier than expected from the roll electrode. Most of such particles will be collected in the middling compartment, while those carrying smaller charge or having larger size will impurify the C product.
- 3) Reprocessing of the middling fraction has a cost that cannot be neglected when large quantities of materials are involved.

Based on the chosen criterion, the optimum levels of the design factors are those for which M is minimum and relatively insensitive to noise factors (i.e., the output/noise ratio is high). Taguchi demonstrated that when the target is a minimum this objective is attained when the following function Y is maximized:

$$Y = -10 \log(\psi^2 + \sigma^2) \quad (1)$$

where ψ is the average and σ^2 is the variance of the responses obtained for each given point of the inner array.

III. MATERIAL AND METHOD

The tests were carried out on a synthetic material, obtained from genuine chopped electric wire wastes processed in the recycling industry. Five samples were prepared (Table I), to correspond to the five experimental points of the outer array of the design. The mass of each sample was 200 g.

A laboratory roll-type corona-electrostatic separator manufactured by CARPCO Inc., Jacksonville, FL, was employed for the experimental study. The positions of the high-voltage electrodes and of the splitters were chosen in accordance with the recommendations of a previous study. The products were collected in three distinct bins: conductor, nonconductor, and middling. Each fraction was weighed on an electronic balance (resolution: 0.1 g).

TABLE II
EXPERIMENTAL RESULTS

No.	Test #	U [kV]	n [min ⁻¹]	c [%]	d [mm]	C [g]	M [g]	NC [g]
1	1111	30	80	5	1.5	9.8	2.6	187.6
2	2111	34	80	5	1.5	10.0	3.6	186.4
3	1211	30	100	5	1.5	10.0	6.0	184.0
4	2211	34	100	5	1.5	10.2	6.4	183.4
5	1121	30	80	45	1.5	88.0	2.8	109.2
6	2121	34	80	45	1.5	87.8	4.0	108.2
7	1221	30	100	45	1.5	88.0	5.8	106.2
8	2221	34	100	45	1.5	87.4	7.0	105.6
9	1112	30	80	5	2.5	10.4*	29.2	160.4
10	2112	34	80	5	2.5	10.8*	29.2	160.0
11	1212	30	100	5	2.5	11.4*	49.6	139.0
12	2212	34	100	5	2.5	11.8*	46.8	141.4
13	1122	30	80	45	2.5	87.6	19.8	92.6
14	2122	34	80	45	2.5	88.6	19.0	92.4
15	1222	30	100	45	2.5	88.2	31.0	80.8
16	2222	34	100	45	2.5	88.8	31.0	80.2
17	1100	30	80	25	2	49.2	12.2	138.6
18	2100	34	80	25	2	48.8	14.0	137.2
19	1200	30	100	25	2	49.2	21.6	129.2
20	2200	34	100	25	2	49.4	23.8	126.8
21	0011	32	90	5	1.5	10.0	4.4	185.6
22	0021	32	90	45	1.5	88.0	4.4	107.6
23	0012	32	90	5	2.5	10.8*	40.0	149.2
24	0022	32	90	45	2.5	87.4	26.8	85.8
25	0000	32	90	25	2	49.2	17.4	133.4
26	0000	32	90	25	2	49.0	16.0	135.0
27	0000	32	90	25	2	49.0	15.8	135.2

A commercial software package (MODDE 5.0, Umetrics AB, Umea, Sweden [22], [23]) was used for the extraction of the model (a second-order polynomial function of the normalized centered values U^* , n^* , d^* , and c^* of the factors under study)

$$y = a_0 + a_1U^* + a_2n^* + a_3d^* + a_4c^* + a_{1,1}U^{*2} + a_{2,2}n^{*2} + a_{3,3}d^{*2} + a_{4,4}c^{*2} + a_{1,2}U^*n^* + a_{1,3}U^*d^* + a_{1,4}U^*c^* + a_{2,3}n^*d^* + a_{2,4}n^*c^* + a_{3,4}d^*c^*. \quad (2)$$

IV. RESULTS AND DISCUSSION

The results of the 27 experiments corresponding to the experimental design in Fig. 2 are given in Table II. The tests were carried out in random order, at stable environmental conditions: 18 °C–19.2 °C and 37.2–38.4 RH%. In all the experiments, the NC fraction was practically copper free (i.e., less than 0.01% of copper impurities), while the C fraction had a copper content >97% (imposed by the customers), in all but five tests, marked with an * in Table II.

A. Classic Analysis Approach

The standard way to analyze the experimental data is to calculate for each experimental point in the inner array two derived responses: the mean value ψ and the variance σ^2 of the

TABLE III
COMPUTATION OF OUTPUT/NOISE RATIO

U [kV]	n [RPM]	MIDDLING [g]					ψ	σ^2	Y
		S11	S12	S21	S22	S00			
30	80	1.3	14.6	1.4	9.9	6.1	6.7	26.05	-18.5
30	100	3.0	24.8	2.9	15.5	10.8	11.4	67.90	-22.9
34	80	1.8	14.6	2.0	9.5	7.0	7.0	23.20	-18.6
34	100	3.2	23.4	3.5	15.5	11.9	11.5	58.13	-22.7
32	90	2.2	20	2.2	13.4	8.7	9.3	46.49	-21.23
32	90					7.9			
32	90					8.0			

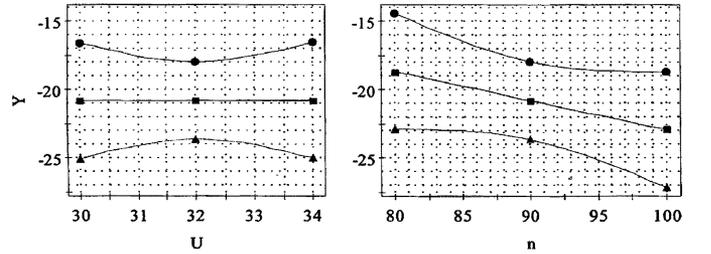


Fig. 3. Plots of the predicted output/noise ratio Y as a function of U and n . The computations were carried out with MODDE, for a confidence level $p = 0.95$.

responses obtained for the five combinations of the noise factors (i.e., the five outer array experiments, corresponding to the five samples on which the separation tests were carried out). The main drawback of this approach is that it does not enable the estimation of the effects of the noise factors and their interactions with the design factors. The computed data contained in Table III indicate only the effects of the design factors on ψ and σ^2 . Thus, it can be observed that, in the chosen experiential domain, the voltage level U has little effect on both ψ and σ^2 , while reducing the speed diminishes simultaneously the mean quantity of middlings and the spread of the responses. It seems that a good separation is achieved at 80 r/min, no matter what the value of the applied voltage between 30–34 kV.

The computation of the function Y (output/noise ratio), the values of which are given in the last column of Table III, makes possible a finer analysis of the situation. A simple model can be derived as

$$Y = -20.786 + 0.025U^* - 2.125n^* + 0.075U^*n^*. \quad (3)$$

The plots of the response Y predicted by the above model are shown in Fig. 3. They convey an unambiguous message: the most robust design is obtained at lower values of the roll speed, with the voltage having little influence on Y when it varies between 30–34 kV.

B. Interaction Analysis Approach

Pertinent information on the interactions between noise and design factors can be extracted from the data presented in

Table III. A regression model can be fitted which contains both types of factors (design and noise) and their interactions

$$\begin{aligned}
 y = & 9.08 + 0.092U^* + 2.03n^* + 6.04d^* - 1.45c^* \\
 & + 0.012U^{*2} + 0.012n^{*2} + 0.242d^{*2} + 0.242c^{*2} \\
 & - 0.042U^*n^* - 0.178U^*d^* + 0.072U^*c^* + 1.18n^*d^* \\
 & - 0.36n^*c^* - 1.31d^*c^*. \quad (4)
 \end{aligned}$$

The statistics of this model are rather good ($R^2 = 0.994$; $Q^2 = 0.659$). The size of the granules and the roll speed have the most important effects on the response of the process: the quantity of middling increases with both d and n (the corresponding coefficients in the regression model being 6.04 and 2.03). The increase of the copper content diminishes M ($a_4 = -1.45$), especially for larger size samples ($a_{3,4} = -1.31$). As expected, a strong interaction exists between n and d ($a_{2,3} = 1.18$), which means that larger quantities of middling are collected from the samples of larger size particles, at higher roll-speeds.

In the case when the model is reduced to its more significant six terms

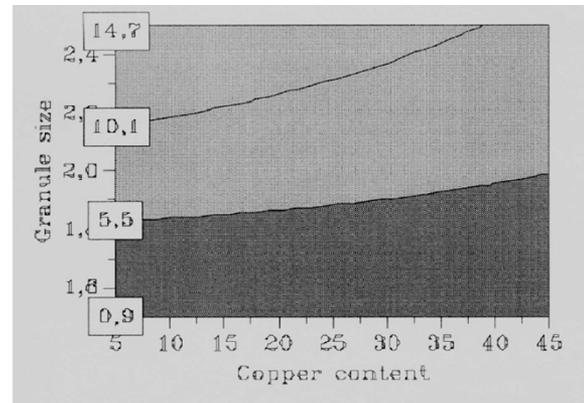
$$\begin{aligned}
 y = & 9.08 + 2.03n^* + 6.04d^* - 1.45c^* + 1.18n^*d^* \\
 & - 0.36n^*c^* - 1.31d^*c^* \quad (5)
 \end{aligned}$$

its predictive ability is further improved, to attain $Q^2 = 0.928$. The contour plots obtained for the simplified model are represented in Fig. 4. They point out that the percentage of middling in the output is very little influenced by the copper content in the input. From a practical point of view, this is a very encouraging observation, as it can be inferred from it that the control variables of the process (the high voltage and the roll speed) do not need to be adjusted when the composition of the cables to be treated varies within a rather extended range of values.

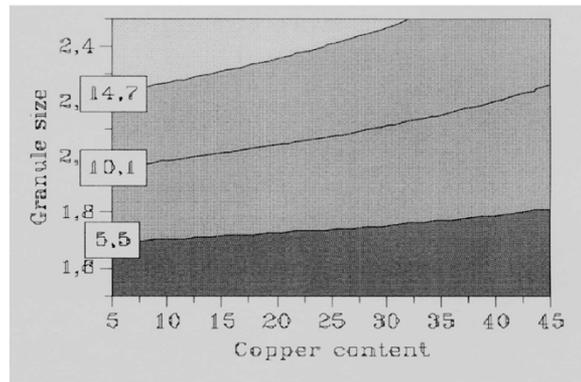
On the contrary, the output of the process seems to be rather sensitive to any modification in the granule size of the materials to be treated. This is especially true for the larger values of the roll speed (100 min^{-1}), where an increase of 50% of the median granule size (from 1.6 to 2.4 mm) would multiply by nearly four the percentage of middling in the output (from 5.5% to more than 20%), at a copper content of 5% in the feed. The physical explanation is simple: the electric image force exerted on an insulating particle decreases proportionally with the square of its radius. As a consequence, it is easier for the centrifugal force to detach the larger particles from the rotating roll and drive them to the middling or even to the conductor bin of the collector. This is why, in tests 11 (#1212) and 12 (#2212), for instance, only 139 and 141.4 g of the 190 g of PVC existing in the feed were collected in the NC product. The mass of PVC detected in the C product (1.6 and 2 g, respectively) significantly affected the purity of the recycled copper (less than 90%). These results confirm the fact that a large quantity of middling is generally accompanied by a poor purity of the recovered copper (the C product).

V. CONCLUSION

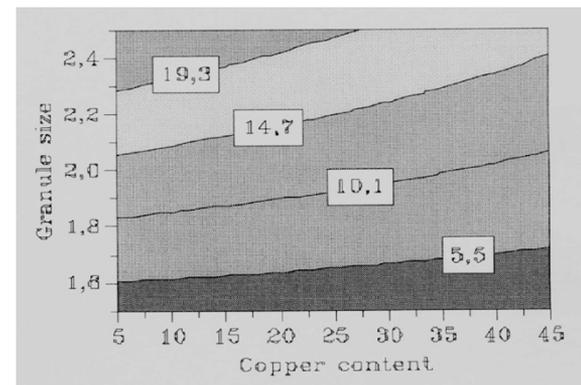
Taguchi's methodology is a powerful tool for the robust design of electrostatic separation processes, within which there is



(a)



(b)



(c)

Fig. 4. Contour plots of the simplified response function (percentage of middling) computed with MODDE, for (a) $n = 80 \text{ min}^{-1}$, (b) $n = 90 \text{ min}^{-1}$, and (c) $n = 100 \text{ min}^{-1}$.

an inherent variability due to fluctuating feed material characteristics. Through the proper selection of the operating conditions of the electrostatic separation installation, the process can be made less sensitive to variations, thus avoiding the costly eventualities of product rejection and/or retreatment.

Further research is needed to determine and subsequently minimize the effects of at least two other groups of factors that can cause variations in process response: 1) diminution of the corona current due to the aging of the coronating elements and the progressive accumulation of dust on their surface and 2) uncontrolled modifications of the environmental conditions (tem-

perature, relative humidity). They will hopefully contribute to the design of more robust processes, and answer the strong industrial demand for reduced sensitivity of the electrostatic separation efficiency to such variations in the operating conditions of a given installation.

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