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MODELING OF ELECTROSTATIC SEPARATION PROCESSES USING TAGUCHI'S EXPERIMENTAL DESIGN METHODOLOGY

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Abstract –Design of experiments is a powerful tool in improving electrostatic separation performances by adjusting the main control factors of the process: the high-voltage level and the roll speed. The aim of the present paper is to analyze the possibility of deriving a mathematical model capable to reflect the effects of a larger number of factors, as well as their main interactions. At first, the main variables of the process were listed and classified in accordance with the ease of controlling them. Taguchi's methodology was then used for chosing the appropriate experiMental design. The objective was to minimize the middling fraction. 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 d.c. high-voltage supply. The samples of processed material were prepared from genuine chopped electric wire wastes (granule size > 1mm and < 2 mm) containing 25% copper and 75% PVC. The experiment consisted of 16 tests, which enabled the derivation of a linear-interaction model comprising 7 variables and 8 interactions.

INTRODUCTION

The optimisation of electrostatic separation processes [1-6] requires the simultaneous control of various electrical and mechanical factors [7-9]: high-voltage level, the electrode configuration, the feed rate, the granule size, the roll speed [10] (Fig. 1).

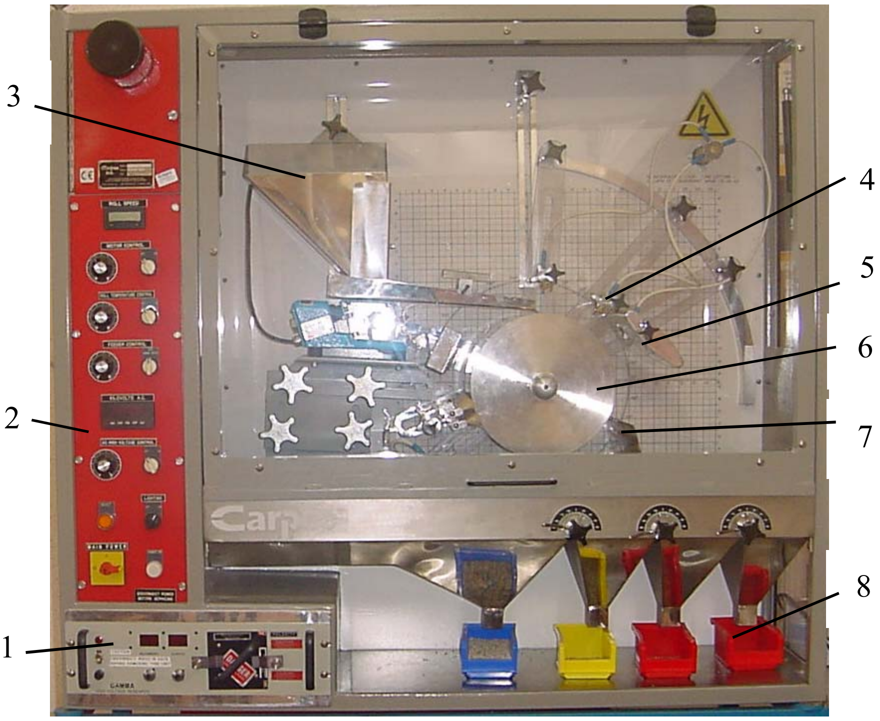


Fig. 1. Roll-type corona-electrostatic laboratory separator (CARPCO Inc., Jacksonville, Fl); 1: high-voltage supply (40 kV, D.C.); 2: control panel; 3: feeder; 4: corona electrode; 5: electrostatic electrode; 6: grounded roll electrode; 7: splitter; 8: collector.

Experimental design techniques have long been used in the optimisation of multi-factorial processes in chemical or metallurgical industries [11, 12]. In two previous papers [13, 14], the author analyzed the peculiarities of these techniques when applied to electrostatic separation processes. The application of such methods requires careful planning, prudent layout of the experiment, and expert analysis of results [15]. Based on years of research and applications, Dr. Genechi Taguchi has standardized the procedure of experimental design and converted it into a much more attractive tool to practicing engineers and scientists [16-19]. Taguchi methodology is particularly suitable for screening a large number of factors to narrow it down for more intensive study by RSM or other similar techniques. This is the case for many practical problems where the purpose is "fine tuning" of a relatively well-known process.

Electrostatic separation is one such process, for which it is not difficult to list the main variables, and indicate those that can be expected to interact. Therefore, the aim of the present paper is to analyze the possibility of using Taguchi methodology for deriving a model capable to reflect the effects of a large number of factors, as well as their main interactions.

PROBLEM FORMULATION USING TAGUCHI METHODOLOGY

In all experimental design techniques, the settings of the various process variables change from one run to another. After conducting such an experiment, the data from all runs in the set taken together are analyzed to determine the effects of the various variables, and – in some cases – the presence of interactions. Two factors are considered to have interaction between them when one has influence on the effect of the other factor respectively.

A thorough examination of the conditions of the industrial application lead to the following list of two-level factors to be studied by experimental design techniques (Fig. 2): high-voltage level U [kV]; roll-speed n [min^{-1}]; angular α_1 [°] and radial s_1 [mm] position of the corona electrode; angular α_2 [°] and radial s_2 [mm] position of the electrostatic electrode; angular position γ [°] of the splitter between the collectors for conductor and middling fractions.

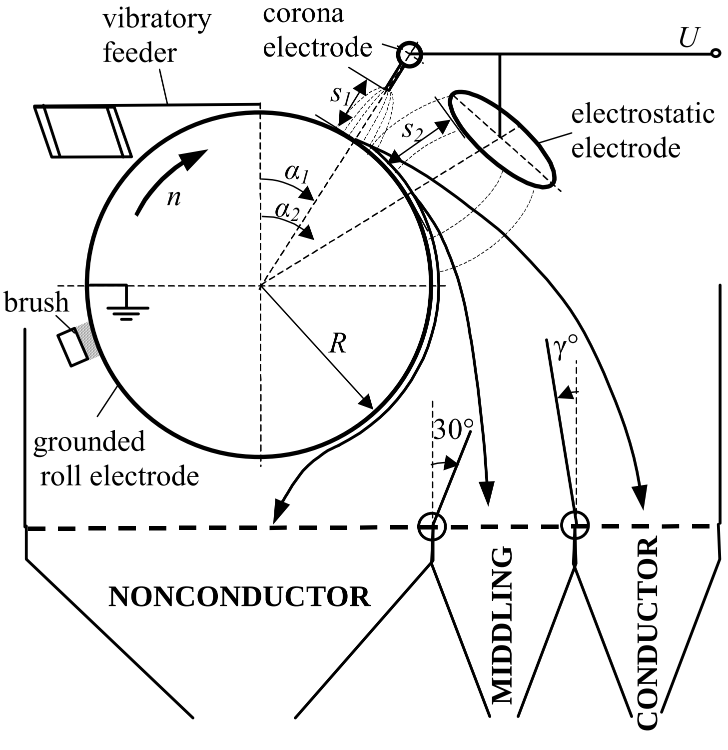


Fig. 2. Control factors of an electrostatic separation process.

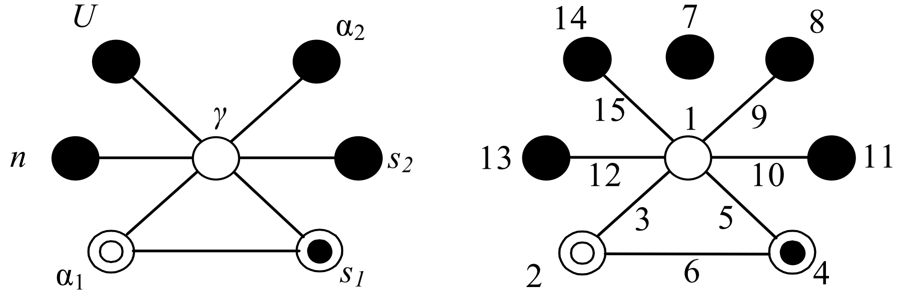
Taguchi experimental designs are based on special matrices, called orthogonal arrays. They are usually identified with a name such as L_8 or L_{16}, to indicate an array with 8 or 16 runs. The classical experimental designs are also based on orthogonal arrays, but they are identified with the superscript indicating the number of variables: 2^3 (8 runs) or 2^4 (16 runs), for 3 or 4 variables, respectively. In most pratical cases, once the number of variables and the number of settings per variable are determined, the task of finding a suitable array is easily reduced to selecting an already-constructed table [15-19].

For modeling a 7-variable peocess with a classical methodology, $2^7 = 128$ runs should be performed, but no assumptions about the presence of interactions are necessary before carrying out such an experimental design. Taguchi methodology leads to a significantly lower number of runs: 8 or 16, depending on the number of considered interactions, but requires some preliminary knowledge of the process. This serves for classifying the factors in four groups, in function of the ease of adjusting their values: 1, very difficult; 2, difficult; 3, easy; 4, very easy. In the L_{16} orthogonal array recommended by Taguchi, for instance, the first column is assigned to a group 1 factor, as it presents only one change of level, the next three columns correspond to group 2 factors, the columns 5 to 8 belong to group 3 factors, the rest being included in group 4.

The first two factors in the list established above (U and n) definetely belong to group 4: they are easily and accurately adjastable by the operator as all modern electrostatic separators employ regulated high-voltage power supplies and fully-controlled AC or DC motor drives. The last factor in the same list (i.e. γ) is very difficult to adjust accurately, as the resolution of the mechanical devices that ensure the angular positioning of the splitter rarely is $< 2°$. Of the four remaining factors, the distance s1 from the corona wire to the roll electrode is the most critical and should be assigned to group 2 or 3. Indeed, the corona current that charges the insulating particles is strongly dependent on this parameter [20]. The angular position of the corona electrode is not that critical to the process [21]. This factor was included in group 3. The last two factors considered in the present study (i.e. α_2 and s_2) are both assignable to group 4.

All the factors are expected to interact with the position of the splitter. The effectiveness of the corona charging of the particles is expected to be influenced by both the angular and the radial position of the corona electrode. Therefore, the interaction between these two factors should be taken into consideration.

The interactions between the factors can be represented by a linear graph, as in Fig. 3,a. The nodes of a Taguchi's graph represent the columns where the interacting factors are assigned and the number associated with the lines indicate the column numbers for the interactions. It can be easily seen that the linear graph of the electrostatic separation process is a subset of Taguchi's linear graph represented in Fig. 3,b. As a consequence, the factor γ will be assigned to column 1, α_1 and s_1 to columns 2 and 4, with their interaction in column 6, α_2 and s_2 to columns 8 and 11, n to column 13 and U to 14.



(a) (b)

Fig. 3. Linear graph representation of the factors under study (a) and the Taguchi's linear graph associated to the L_{16} orthogonal array (b).

The linear-interaction model corresponding to Taguchi's linear graph associated to L_{16} orthogonal array (Fig. 3,b) can be written as follows:

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_{1,2} x_1 x_2 + a_4 x_4 + a_{1,4} x_1 x_4 + a_{2,4} x_2 x_4 + a_7 x_7 + a_8 x_8 + a_{1,8} x_1 x_8 + a_{11} x_{11} + a_{1,11} x_1 x_{11} + a_{13} x_{13} + a_{1,13} x_1 x_{13} + a_{14} x_{14} + a_{1,14} x_1 x_{14} \qquad (1)$$

with $a_0 = (\sum y_k)/16$; $a_i = (\sum x_{ik}\, y_k)/16$; $i = 1\ldots15$; $a_{1,2} = a_3$; $a_{1,4} = a_5$; $a_{2,4} = a_6$; $a_{1,8} = a_9$; $a_{1,11} = a_{10}$; $a_{1,13} = a_{12}$; $a_{1,14} = a_{15}$; where y_k is the value of the response function for the test k (k = 1,..., 16). As only 7 factors are considered in the present study:

$$x_1 = \gamma^*,\ x_2 = \alpha_1^*,\ x_4 = s_1^*,\ x_8 = \alpha_2^*,\ x_{11} = s_2^*,\ x_{13} = n^*,\ x_{14} = U^* \qquad (2)$$

the column 7 of L_{16} orthogonal array is not employed, and $a_7 = 0$.

MATERIAL AND METHOD

A laboratory roll-type corona-electrostatic separator manufactured by CARPCO Inc., Jacksonville, Florida, was employed for the experimental study. The tests were carried out on a synthetic material, obtained from genuine chopped electric wire wastes processed in the recycling industry (25% copper, 75% insulating materials, particle size > 1 mm and < 2 mm). The mass of each sample was 400 g. The products were collected in three bins: conductor, nonconductor, and middling.

RESULTS

The results of the 16 experiments are given in Table 1. All the tests were carried out on the same sample, at stable environmental conditions: 19 – 21°C, 26 – 40 RH%.

Table 1. Results of the 16+3 experiments of the first design.

No	γ [°]	α_1 [°]	s_1 [mm]	α_2 [°]	s_2 [mm]	n [min^{-1}]	U [kV]	m¤ [g]
1	-8	25	40	60	70	80	30	4.3
2	-8	25	40	70	80	100	34	9.7
3	-8	25	50	60	70	100	34	11.0
4	-8	25	50	70	80	80	30	8.4
5	-8	30	40	60	80	80	34	8.4
6	-8	30	40	70	70	100	30	10.5
7	-8	30	50	60	80	100	30	41.5
8	-8	30	50	70	70	80	34	4.2
9	-4	25	40	60	80	100	30	17.9
10	-4	25	40	70	70	80	34	9.2
11	-4	25	50	60	80	80	34	8.5
12	-4	25	50	70	70	100	30	25.5
13	-4	30	40	60	70	100	34	22.0
14	-4	30	40	70	80	80	30	10.0
15	-4	30	50	60	70	80	30	16.8
16	-4	30	50	70	80	100	34	18.1
17	-6	27.5	45	65	75	90	32	12.6
18	-6	27.5	45	65	75	90	32	11.7
19	-6	27.5	45	65	75	90	32	11.6

¤ m is the mass of the product collected in the middling fraction.

The derived linear-interaction model ($y = m$) is:

$$y = 14.075 + 1.875\,\gamma^* + 2.313\,\alpha_1^* + 1.588\,\gamma^*\alpha_1^* + 2.625\,s_1^* + 1.4\,\gamma^* s_1^* - 0.283\,\alpha_1^* s_1^* - \\ - 2.175\,\alpha_2^* - 1.875\,\gamma^*\alpha_2^* + 1.188\,s_2^* + 2.713\,\gamma^* s_2^* + 5.4\,n^* + \\ + 0.525\,\gamma^* n^* - 2.738\,U^* - 1.188\,\gamma^* U^*. \qquad (3)$$

According to this first model, the optimum of the process (i.e., the smallest amount of middling) should be obtained for $\gamma = -8°$; $\alpha_1 = 25°$; $s_1 = 40$ mm; $\alpha_2 = 70°$; $s_2 = 70$ mm; $n = 80$ min^{-1}; $U = 34$ kV.

DISCUSSION

A delicate problem is the determination of the factor levels. Preliminary exploratory experiments are necessary for establishing the domain of variation for γ, U, and n. Fortunately, the availability of data on similar previous applications of the electrostatic separation technology facilitates this task for the other factors. Thus, α_1 should not be less than 25° (otherwise it would be too close to the exit of the vibratory feeder, and the electric wind would prevent the transfer of the particles to the surface of the roll electrode) or more than 30° (not to be too close to the electrostatic electrode, the proximity of which would modify the conditions of corona onset).

The inter-electrode spacing s_1 has to be large enough for the corona discharge to affect an extended angular region on the surface of the roll electrode ($s_1 > 40$ mm), but is limited by the available high-voltage supply ($s_1 < 50$ mm). Based on similar considerations regarding the configuration of the electrostatic field, $60° < \alpha_2 < 70°$, and $70 \text{ mm} < s_2 < 80$ mm.

An important advantage of Taguchi's approach is the possibility to simultaneously analyse the effects and the predicted interactions of a great number of influencing factors, by examining the coefficients of the model (3). Thus, the quantity of middlings diminishes when applying higher voltages U ($a_{14} = -2.738$), and increases for larger interelectrode spacings s_1 ($a_4 = 1.4$), s_2 ($a_{11} = 1.188$). The physical explanation is simple: the electric field is stronger for higher voltages and smaller interelectrode spacings, enhancing the particle charging effects and the electric separation forces.

The model reveals two less-easy-to-predict effects. More particles are collected in the middling product when increasing α_1 ($a_2 = 2.313$) and decreasing α_2 ($a_8 = -2.175$). This means that the separation is more effective if the corona and electrostatic electrodes are located closer respectively to the vertical and the horizontal symmetry plane of the roll electrode. This implies smaller α_1, to achieve the ionic charging of the insulating particles as soon as they are fed onto the carrier electrode, and larger α_2, to extend the region of action of the electric field on the conducting particles.

Larger quantities of middlings are collected when increasing n ($a_{13} = 5.4$), as the centrifugal force tends to detach sooner the insulating particles "pinned" to the surface of the rotating roll electrode. In the domain considered for the experiment, the effect of roll speed is by far the greater. As lower speeds require smaller feed rates, the decrease of n below a certain limit would be accompanied by an unacceptable diminution of the amounts of recovered conductor and nonconductor products. In order to further investigate this issue, a different response function should be considered: (mass of conductor + nonconductor fractions)x roll speed , but this is beyond the scope of the present study.

The increase of the splitter angle γ expends the collecting zone of the middling product ($a_1 = 1.875$). Most of the other factors interact rather significantly with γ, as indicated by the respective coefficients of the model: $a_{1,2} = 1.588$; $a_{1,4} = 1.4$; $a_{1,8} = -1.875$; $a_{1,11} = 2.713$; $a_{1,14} = -1.188$.

CONCLUSIONS

Taguchi's methodology provides an alternative to standard factorial design. Its peculiarity resides in the fact that the selection of the experimental design is made from examination of linear graphs, allowing the investigation of the desired interaction effects, based on process knowledge. The physical phenomena on which "classical" electrostatic separation processes are based are known well enough to facilitate the set up of linear graphs for representing the input variables and the predicted interactions between them.

The experimental design presented in this paper clearly proved that the linear-interaction models of the electrostatic separation process can reflect the effects of the main factors in a manner that is satisfactory to most cases of practical interest. At the same time, it pointed out the limitations of Taguchi's method, which deliberately and sometimes arbitrarily neglects some of the interactions that might be nevertheless relevant to the process.

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