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Using experimental designs for modelling of intermittent air filtration process

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Abstract Identification of the optimal operating conditions and evaluation of their robustness are critical issues for industrial processes. A standard procedure, for modelling a laboratory-scale wire-to-cylinder electrostatic precipitator and for guiding the research of the set point, is presented. The procedure consists of formulating a set of recommendations regarding the choice of parameter values for electrostatic precipitation. The experiments were carried out on a laboratory cylindrical precipitator, built by one of the authors, with samples of wood particles. The parameters considered are the applied high voltage U , the air flow F , and the quantity of dust in air m . Several “one-factor-at-a-time” followed by factorial composite design experiments were performed, based on the following three-step strategy: 1) Identify the domain of variation of the variables; 2) Determine the mathematical model of the process outcome; 3) Validation of the mathematical model and optimisation of the process.

Keywords design of experiments, electrostatic precipitator, experimental modelling, high voltage

1 Introduction

Electrostatic precipitation is an effective method used to eliminate solid polluting particles (such as dust and ashes) or liquids (oil mist for example) contained in gases injected into our environment [1–5]. No other process of filtering is as effective as the electrostatic process; its applicability currently extends to the viable spaces (houses, offices, hospitals, etc.) and workshops (engine

rooms) [6], considering its low electric power energy consumption and its great efficiency of air filtration (up to 99.9%).

For each application, the modelling and identification of the optimal operating conditions are crucial questions. The modelling of electrostatic precipitator (ESP) has been the subject of many papers [7–13], but none has used the method of experimental designs which proved to be a good tool for the optimization of such processes. The method used in this paper is to determine a mathematical model for the ESP process of a laboratory model, which will be used to determine optimal values of process factors and also for predicting the outcome of the process for randomly values of the factors.

The working principle of an electrostatic precipitator (ESP) can be easily explained with the cylindrical model of ‘Cottrell’ type (Fig. 1). It consists of a grounded vertical metal cylinder (the collecting electrode) and a wire (the discharge electrode) suspended along its axis by an insulator bushing. The gas containing particulate pollutants is introduced into the ESP from a gas inlet at the bottom of the cylinder and flows upward in the cylinder through the inter-electrodes gap. The particles are bombarded by ions from the discharge electrode (corona wire) and are strongly charged; they are then driven by electrostatic force toward the collecting electrode and are deposited on its inner surface [3,4]. A mechanical rapping (battement) is provided on the collecting electrode to eliminate the polluting layer so that it falls down into the hopper, and finally removed out of the precipitator.

2 Experimental designs applied to electrostatic precipitation

“Experimental design” is a mathematical methodology based on statistical analysis which is useful for several objectives, whatever the field of application: screening, modelling, optimization and evaluation of the robustness [14,15]. Used at the beginning of research on a new

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application, experiments of screening are usually employed to explore a significant number of factors to evaluate their effects on the responses or to identify their suitable intervals of variation. In the context of this study, the experiments of screening were employed with a little different aim: to define with more precision the domain of variation of factors which are easily controllable in our laboratory model: the level of high voltage U kV; the level of air flow F m³/min; the mass of particles to filter m g.

The process being relatively well-known, we expect that classical experiments “one-factor-at-a-time” will be more effective than any other method.

The step of optimization of this experimental procedure should allow the identification of the operation set-point, i.e. values of factors for which response of the process is maximum, minimum, or close to a target. For electrostatic air filtration, maximization of the process outcome is the criterion considered for modelling and optimization. The composite centred faces design CCF is generally used, because it proposes models of quadratic polynomials. With such models, the response of the process is expressed there according to the factors u_i ($i = 1, 2, \dots, e$):

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

A normalized centred value can be defined for each factor as follows:

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

where

$$u_{ic} = \frac{u_{imax} + u_{imin}}{2}, \Delta u_i = \frac{u_{imax} - u_{imin}}{2}. \quad (3)$$

With these notations, the function of response becomes:

$$y = f(x_i) = a_0 + \sum a_i x_i + \sum a_{ij} x_i x_j + \sum a_{ii} x_i^2, \quad (4)$$

where x_i can obviously take only the values: -1 (for minimal input value x_{imin}) or $+1$ (for maximal input value x_{imax}).

For the factors considered in the current study: $x_1 = U^*$, $x_2 = F^*$, $x_3 = m^*$ the quadratic model will take the following form:

$$\begin{aligned} y = & a_0 + a_1 U^* + a_2 F^* + a_3 m^* + a_{12} U^* F^* \\ & + a_{13} U^* m^* + a_{23} F^* m^* + a_{11} U^{*2} \\ & + a_{22} F^{*2} + a_{33} m^{*2}. \end{aligned} \quad (5)$$

If the response y considered is the outcome of the process, optimization means the maximization of Eq. (5). Software MODDE 5.0 (Umetrics, Sweden) [16] determines the mathematical model for the response and allows analysis for its optimization.

We used the software MODDE 5.0 (Umetrics AB, Umea, Sweden), which is a Windows program for the

creation and evaluation of experimental designs. The program assists the user on the interpretation of the results and prediction of the responses. It calculates the coefficients of the mathematical model, draws surfaces of response (RSM) and identifies the best adjustments of the parameters for optimizing the process.

Moreover, the program calculates two significant statistical criteria which make it possible to validate or not the mathematical model:

1) The predictive power is given by Q^2 . This is a measure of how well the model will predict the responses for new experimental condition.

2) The goodness of fit parameter given by R^2 .

A good mathematical model must have criteria Q^2 and R^2 with the numerical value closes to the unit.

3 Experimental device and materials

To simulate the operation of the industrial devices of electrostatic precipitation, we realized a laboratory model of filtration (Fig. 1). It consists of a cylinder of aluminium (length $L = 50$ cm and diameter $D = 8$ cm), connected to the ground. A central wire of 1 mm diameter is connected to a direct-current high voltage supply ($U_{max} = 50$ kV, $I_{max} = 10$ mA). To maintain the wire in a vertical position, well tended, we placed at its bottom end a weight of mass $m = 1.5$ kg. An insulating hopper is used to recover the product (polluting particles) after the operation of filtering.

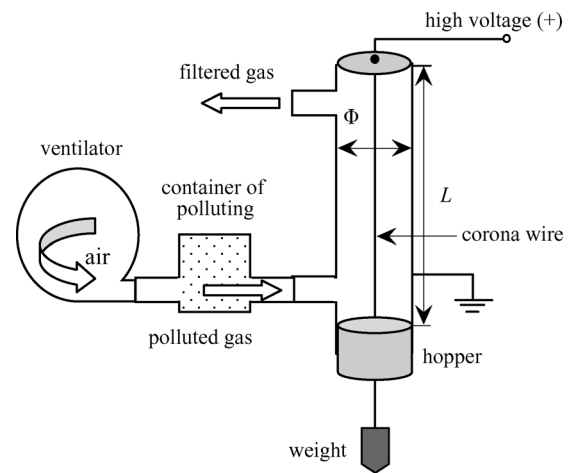


Fig. 1 Descriptive representation of the laboratory experimental device

The polluting product (wood particles) is put in a tank placed upstream of a ventilator, this one being used to drive back the air in the cylinder, inside the ESP. The ventilator (air flow max = 2.3 m³/min, $U = 220$ V) “breath” the polluting product inside the cylinder, which is more or less retained according to the collecting efficiency of the process.

A micro-ammeter (FLUKE 867B, $I_{max} = 10$ A) and a high voltage probe (Metrix-HT212-typeB) are used to

measure the current of the corona discharge and the applied high voltage, respectively. The outcome (efficiency) η is calculated using following relation:

$$\eta(\%) = \frac{m_i - m_s}{m_i} \times 100, \tag{6}$$

where m_i : total mass introduced into ESP, m_s : not filtered mass recovered at exit of the clean gas.

The mass was measured using digital balance of resolution 0.1 g. All tests were carried out under stable environmental conditions: 18°C–20°C, 40–50 RH%.

An experimental procedure of three steps was adopted [17,18]:

Step 1 Define domain of variation of the factors (U_{\min} and U_{\max} , F_{\min} and F_{\max} , m_{\min} and m_{\max}) with three experiments “one-factor-at-a-time”:

Experiment 1.1 Voltage U variable (5 to 35) kV, with constant air flow $F = 1 \text{ m}^3/\text{min}$ and a mass of particles to filter constant $m = 10 \text{ g}$.

Experiment 1.2 Air flow F variable (0.5 to 1.75) m^3/min , with a constant voltage $U = 25 \text{ kV}$ and a mass of particles to filter constant $m = 10 \text{ g}$.

Experiment 1.3 Mass of particles to filter m variable (10 to 70) g, with a constant voltage $U = 25 \text{ kV}$ and a constant air flow $F = 1 \text{ m}^3/\text{min}$.

Step 2 Model ESP process by using a composite centred faces design CCF.

Step 3 Validate experimental modelling and define set-point operation.

4 Results and discussion

Step 1 Variation domain of factors

Results of Experiments 1.1, 1.2 and 1.3 are illustrated in Figs 2, 3 and 4 (for more precision, each experiment was done twice). These data were used for definition of the variation domain of U , F and m for Step 2 of the experimental procedure. Thus, $U_{\min} = 26 \text{ kV}$ and $U_{\max} = 30 \text{ kV}$

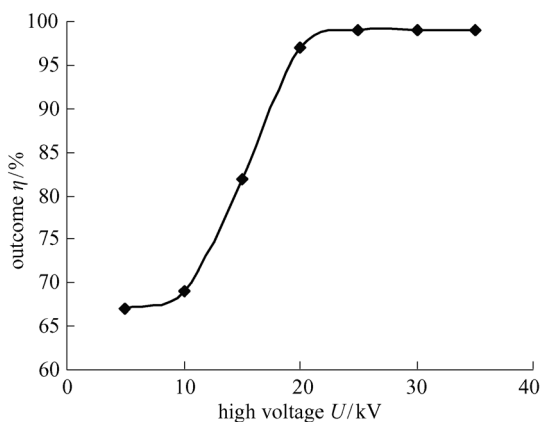


Fig. 2 Variation of process outcome according to high voltage U

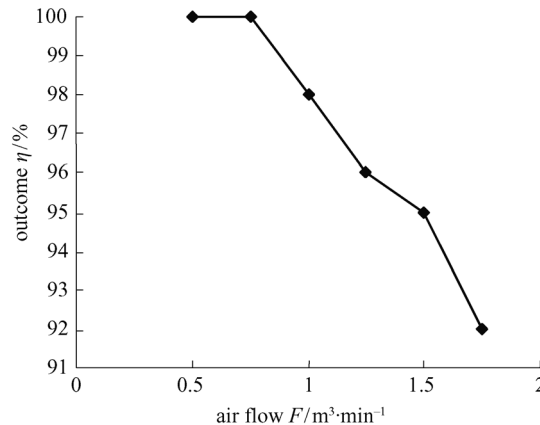


Fig. 3 Variation of process outcome according to air flow F

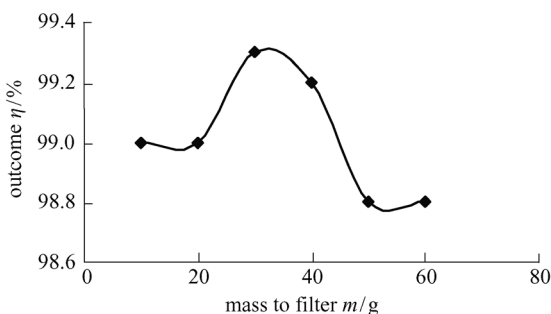


Fig. 4 Variation of process outcome according to mass m

were selected as limit values for the voltage. The variation domain of air flow and the mass to be filtered were defined as follows: $F_{\min} = 0.8 \text{ m}^3/\text{min}$, $F_{\max} = 1.2 \text{ m}^3/\text{min}$ and $m_{\min} = 10 \text{ g}$, $m_{\max} = 30 \text{ g}$.

Step 2 Modelling of the process outcome

The conditions of Step 2 were established by taking in consideration results obtained in Step 1, to assign the limiting values to each variable, and to calculate the respective central values. Values of the central point are calculated as follows:

$$U_c = (U_{\min} + U_{\max})/2, F_c = (F_{\min} + F_{\max})/2,$$

$$m_c = (m_{\min} + m_{\max})/2,$$

$$U_c = (26 + 30)/2 = 28 \text{ kV},$$

$$F_c = (0.8 + 1.2)/2 = 1 \text{ m}^3/\text{min},$$

$$m_c = (10 + 30)/2 = 20 \text{ g}.$$

The main advantage of CCF composite designs is the ability to carry out the experiments sequentially, i.e. to try initially modelling the process with a polynomial of first order [12]. The first step consists thus in a full factorial design. If the first order model is validated, we stop modelling; if not, we continue modelling with a polynomial of second order using a CCF composite design.

In the case of a design with 3 factors, the full factorial design (first order model) corresponds to the experiments

located at the top of the cube (square points A, B, \dots, H) and 3 identical experiments done in the central point M (star point) (Fig. 5). The CCF composite design (second order model) corresponds to the 11 experiments of the factorial design, plus 6 experiments located in the centres of the cube faces (round points a, \dots, f). Thus, the CCF composite design with 3 factors includes 17 experiments.

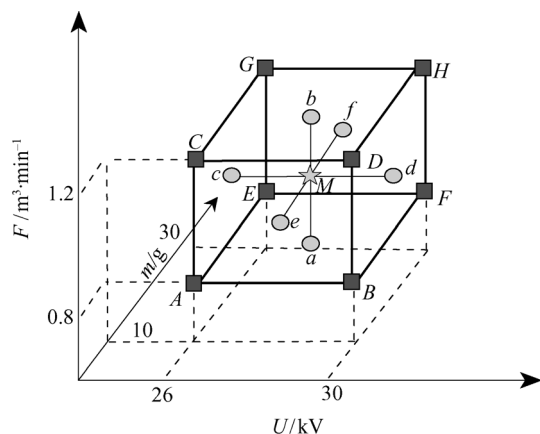


Fig. 5 Diagram of experiments of a CCF design with 3 factors: voltage U ($U_{\min} = 26$ kV and $U_{\max} = 30$ kV), air flow F ($F_{\min} = 0.8$ m³/min and $F_{\max} = 1.2$ m³/min), mass to filter m ($m_{\min} = 10$ g and $m_{\max} = 30$ g)

Results of experiments of the composite design are given in Table 1. MODDE 5.0 gives low values of criteria R^2 and Q^2 ranging from 0.6 and 0.8 (see Step 3). Consequently, mathematical models of first order (factorial design) for process outcome η cannot be validated. Thus we must carry out six additional experiments (Exp. 12–17 of Table 1) to accomplish a CCF composite design.

Table 1 Results of experimental composite design CCF

		No. Exp.	U/kV	$F/\text{m}^3 \cdot \text{min}^{-1}$	m/g	$\eta/\%$
CCF design	factorial design	1	26	0.8	10	99.5
		2	30	0.8	10	100
		3	26	0.8	30	99.8
		4	30	0.8	30	99.7
		5	26	1.2	10	99.0
		6	30	1.2	10	99.0
		7	26	1.2	30	99.0
		8	30	1.2	30	98.3
		9	28	1.0	20	99.5
		10	28	1.0	20	99.5
		11	28	1.0	20	99.5
	12	26	1.0	20	99.0	
	13	30	1.0	20	99.0	
	14	28	1.0	10	100	
	15	28	1.0	30	99.7	
	16	28	0.8	20	100	
	17	28	1.2	20	99.0	

The mathematical model given using CCF design, proposed by the software MODDE 5.0, is:

$$y = 99.51 - 0.03U^* - 0.1m^* - 0.47F^* - 0.52U^{*2} + 0.32m^{*2} - 0.02F^{*2} - 0.16U^*m^* - 0.14U^*F^* - 0.09m^*F^* \quad (7)$$

Step 3 Validation of the mathematical model

When the mathematical model is determined, we now validate it while carrying out following checks:

1) Validation results of all experiments: graph of Fig. 6, given by MODDE 5.0, makes it possible to check and detect any “dubious” result which would be obtained with a badly made experiment (measurement errors for example). As all experiments are inside the field delimited by the borders (outliers), all the results are therefore validated.

2) Check predictive (Q^2 criterion) and experimental (R^2 criterion) quality of the mathematical model: when the values of Q^2 and R^2 are close to the unit, the model is considered as good and can be used for optimization and prediction. As the values of these two criteria according to the model given by Eq. (7), calculated by MODDE 5.0, are respectively $Q^2 = 0.966$ and $R^2 = 0.996$, the model can thus be used to predict and optimize the process.

According to this model, the operation set-point, i.e., the optimum of the process corresponding to a best performance, should be obtained for $U = 29.2$ kV; $F = 0.8$ m³/min; $m = 10$ g. Moreover, we can say that in the selected intervals of the three factors, the most influent factor of ESP is air flow F which is associated with a high coefficient in the mathematical model (0.47). In addition, the outcome which depends very little on the voltage U (coefficient = 0.03) and mass m (coefficient = 0.1), is very influenced by the square of voltage U^2 which is associated with the highest coefficient (0.52) and the square of polluting mass m^2 also (coefficient = 0.32).

In order to really check the predictive quality of the model, we carried out 3 experiments with randomly values of U , F and m (with 2 tests for each experiment), which we compared with values predicted by the mathematical model. Results deferred in Table 2 confirm the good predictive quality of the mathematical model obtained using experimental designs methodology.

We can thus conclude that the mathematical model expressed by Eq. (7) is of good experimental and predictive quality. It can be used for optimization of the process while factors remaining in the intervals fixed in Step 2 for the experimental design.

5 Conclusions

We presented in this paper an experimental procedure which we propose to use in order to model and optimize the process of electrostatic precipitation. This procedure,

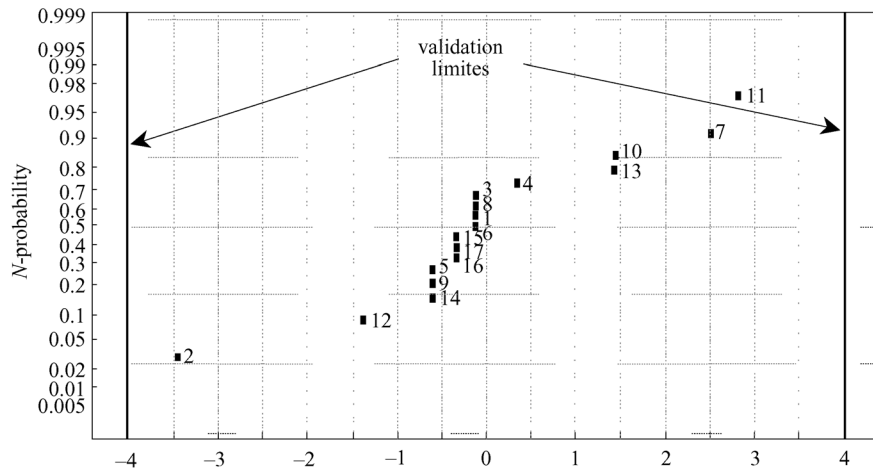


Fig. 6 Graph to validate experiment's results

Table 2 Comparison between experimental and predicted values

U/kV	F/m ³ ·min ⁻¹	m/g	test 1 η/%	test 2 η/%	predicted values η/%	
					low	high
27.0	1.1	15	99.3	99.3	99.26	99.35
29.0	0.9	25	99.6	99.8	99.60	99.69
28.5	1.15	22	99.1	99.1	99.00	99.11

based on the method of experimental designs, makes it possible to delimit domains of variation of the variable factors and then to model the outcome of the precipitator with a mathematical model which is validated by checking some criteria. The obtained models can then be used to determine optimal values of the various parameters and to predict outcome of the precipitator which would be obtained for randomly values of the factors. This methodology can be applied for the design of geometrical dimensions of ESP like height and diameter of cylindrical precipitator. It can also be used for optimization in other electrical devices.

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