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RESEARCH ARTICLE

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Using experimental designs for modelling of intermittent air filtration process

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 m^3/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,..., 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

$$u_{ic} = \frac{u_{i\max} + u_{i\min}}{2}, \Delta u_i = \frac{u_{i\max} - u_{i\min}}{2}. \quad (3)$$

With these notations, the function of response becomes:

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

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

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:

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

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.

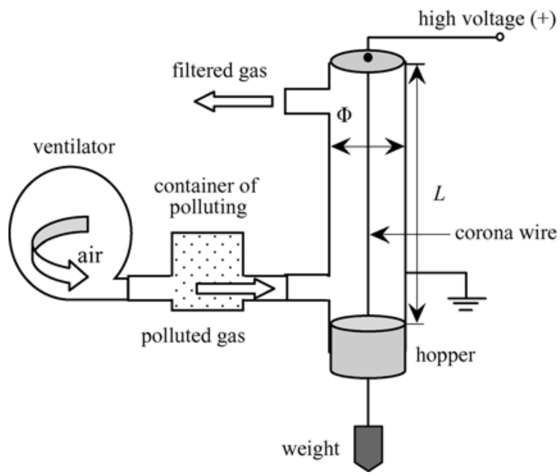

Fig. 1 Descriptive representation of the laboratory experimental device

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 m^3/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