Optimisation of the intermittent operation of a wire-cylinder electrostatic precipitator

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Abstract. Intermittent operation mode is specific to electrostatic precipitators (ESP) used in workshops where the polluting product is produced in a discontinuous way. The present work aimed at validating a standard procedure for modelling and optimisation of such a wire-cylinder ESP, using an appropriate method of experimental design. The experiments were carried out with samples of micronized wood, using a laboratory cylindrical ESP built by one of the authors. The factors considered in the study were the applied high voltage \( U \) (kV), the air flow \( F \) (m\(^3\)/h), the mass of pollutant at the input of the ESP \( m_i \) (g) and the size of particles \( S \) (µm). Several “one-factor-at-a-time” experiments followed by a factorial composite design were performed, in order to identify the domain of variation of each factor and determine the mathematical model of the process.

1. Introduction

Electrostatic precipitation is an effective method to prevent solid or liquid particles (such as fly-ash, dust, oil mist) to pollute our working or living environment [1]. Besides the huge electrostatic filters that purify the flue gases of cement plants, foundries or thermal power stations, many smaller-size units have been developed for the treatment of ambient air in workshops, offices, hospitals, and the like, at very low electric energy consumption and high particle retention efficiency (up to 99.9 %).

For each application, modeling and identification of the optimal operating conditions is a crucial issue. Modeling of ESP was subject of many papers [2-4], but none addressed the optimization of the process when the pollutant is produced in a discontinuous way. This operation mode is specific to ESP used in welding or joinery workshops. In this work an appropriate method of experimental design is employed to determine the mathematical model of such an intermittent ESP, and predict the values of the control factors that would maximize the air filtration efficiency.

2. Experimental set-up and material

A laboratory scale wire-cylinder ESP, build up by one of the authors, was used for the experimental study (figure 1). It consisted of a grounded tubular cylinder of aluminium (length \( L = 50 \) cm, diameter \( \Phi = 8 \) cm), and a co-axial wire (diameter \( d = 1 \) mm) connected to a positive DC high voltage supply (\( U_{\text{max}} = 40 \) kV, \( I_{\text{max}} = 10 \) mA).
For each experimental run, a well-defined mass \( m_i \) of polluting product (micronized wood) was blown from a container located upstream of a ventilator (maximum air flow = 2.3 m\(^3\)/h, at \( U = 220 \) V) connected to the inlet of the ESP. In order to simulate a filtration process characterized by discontinuous generation of the pollutant, the electric motor of the ventilator was turned off after less than 1 min of operation. A hopper was used to recover the polluting particles after filtration.

The outcome of the process (i.e. the air filtration efficiency) \( \eta \) was calculated with the formula:

\[
\eta(\%) = \frac{m_i \cdot m_s}{m_i} \times 100
\]

where \( m_i \) was the mass of pollutant that entered the ESP, and \( m_s \) designated the mass of pollutant recovered in the hopper at exit of the ESP. The masses were measured using a digital balance of resolution 0.1 g. A multimetre (FLUKE 867B) and a high voltage probe (Metrix-HT212-typeB) were used to measure the applied voltage. All tests were carried out under stable ambient conditions: temperature 18 - 20°C, relative humidity 40 – 50%.

3. Experimental design applied to the modelling of electrostatic precipitation

Experimental design is a structured, organized method for determining the relationship between a number of factors affecting a process and the output of that process. Regardless of the domain of application, this methodology is useful for three objectives: screening, optimization, and robustness testing [5, 6]. Employed at the beginning of the investigation of a new application, screening experiments are commonly designed to explore many factors, in order to evaluate their effects on the responses. In the context of this study, the screening experiments were employed with a slightly different purpose in mind: defining the domain of variation of three of the factors that can be easily adjusted in both a laboratory and an industrial environment, i.e. the high voltage \( U \) [kV]; the air flow \( F \) [m\(^3\)/h], and the mass of pollutant \( m_i \) [g].

Optimization stage of an experimental procedure should enable the identification of the “set-point”, i.e. the values of the control factors for which the response of the process is maximum, minimum, or approaches a target [7, 8]. For electrostatic precipitation processes, the maximization of the air filtration efficiency \( \eta \) fraction could be the chosen criterion of evaluation. In the present work, the set-point was identified by using the response surface method in conjunction with a composite design [7], which supports quadratic polynomial models.
4. Results and discussion

4.1. Experimental domain. The results of three “one-factor-at-a-time” experiments are represented in figures 2, 3 and 4. The limits of variation of the three factors were established as follows: \( m_{\text{imin}} = 20 \text{ g} \); \( m_{\text{imax}} = 44 \text{ g} \); \( U_{\text{min}} = 20 \text{ kV} \); \( U_{\text{max}} = 30 \text{ kV} \); \( F_{\text{min}} = 0.8 \text{ m}^3/\text{h} \); \( F_{\text{max}} = 1.2 \text{ m}^3/\text{h} \). The wood particles were characterized by an average size \( S_{\text{imin}} = 80 \mu\text{m} \); \( S_{\text{imax}} = 160 \mu\text{m} \).

4.2. Modelling of the process. The results of the twenty-seven experiments of a composite design are given in Table 1. The mathematical model of the response, i.e the air filtration efficiency, obtained with an experimental design dedicated software (MODDE 5.0, by Umetrics, Umea, Sweden) is:

\[
y = 99.08 + 0.31 U^* - 0.69 F^* - 0.12 m_i^* + 0.01 S^* + 0.13 U^*^2 - 0.25 F^*^2 + 0.13 m_i^*^2 \\
- 0.12 S^*^2 + 0.06 U^*F^* - 0.12 U^*m_i^* + 0.09 U^*S^* - 0.1 F^* m_i^* + 0.11 F^*S^* + 0.07 m_i^*S^*
\]

where \( U^*, F^*, m_i^*, S^* \) are the normalised centered values of \( U, F, m_i, S \), as defined in [5, 9]. Within the limits of the experimental domain considered in this study, the most influential factors of ESP were the air flow \( F \) and the applied high voltage \( U \) (the respective coefficients in the model are the highest).

This model has good statistics, as both the goodness of fit parameter \( R^2 \) and the goodness of prediction parameter \( Q^2 \) are close to 1: \( R^2 = 0.979 \) and \( Q^2 = 0.883 \). According to this model, the operation set point, i.e. the optimum of the process corresponding to the maximum air filtration efficiency, should be obtained for \( U = 30 \text{ kV} \) and \( F = 0.8 \text{ m}^3/\text{h} \).

In order to obtain a supplementary validation of the model, three experiments were carried out at randomly chosen values of \( U, F, m_i, S \) (with 2 tests for each experiment). The experimental data were compared with the values predicted by the mathematical model. The results deferred in Table 2 confirm the good predictive quality of the mathematical model.

5. Conclusions

ESP is a multiple-factor process that can be modelled and optimised by using appropriate methods of experimental design. The availability of user-friendly software tools simplifies the task of the investigator, who is no longer constrained in the application of this methodology by the complexity of statistical analysis of the experimental data. It was thus possible to determine the values of the control factors (high voltage and flow-rate) that optimize the intermittent operation of a laboratory ESP.
Table 1. Results of the CCF experimental design.

| Test N° | U (kV) | F (m³/h) | m (g) | S (µm) | η (%) | Test N° | U (kV) | F (m³/h) | m (g) | S (µm) | η (%) |
|---------|--------|----------|-------|--------|-------|---------|--------|----------|-------|--------|-------|
| 1       | 20     | 0.8      | 20    | 80     | 98.0  | 15      | 20     | 1.2      | 44    | 160    | 99.0  |
| 2       | 30     | 0.8      | 20    | 80     | 99.0  | 16      | 30     | 1.0      | 32    | 120    | 99.0  |
| 3       | 20     | 1.2      | 20    | 80     | 99.3  | 17      | 20     | 1.0      | 32    | 120    | 99.0  |
| 4       | 30     | 1.2      | 20    | 80     | 99.8  | 18      | 30     | 1.0      | 32    | 120    | 98.0  |
| 5       | 20     | 0.8      | 44    | 80     | 98.0  | 19      | 25     | 0.8      | 32    | 120    | 99.0  |
| 6       | 30     | 0.8      | 44    | 80     | 98.7  | 20      | 25     | 1.2      | 32    | 120    | 99.3  |
| 7       | 20     | 1.2      | 44    | 80     | 99.0  | 21      | 25     | 1.0      | 20    | 120    | 99.8  |
| 8       | 30     | 1.2      | 44    | 80     | 99.5  | 22      | 25     | 1.0      | 44    | 120    | 98.0  |
| 9       | 20     | 0.8      | 20    | 160    | 99.75 | 23      | 25     | 1.0      | 32    | 80     | 98.7  |
| 10      | 30     | 0.8      | 20    | 160    | 99.0  | 24      | 25     | 1.0      | 32    | 160    | 99.0  |
| 11      | 20     | 1.2      | 20    | 160    | 99.5  | 25      | 25     | 1.0      | 32    | 120    | 99.5  |
| 12      | 30     | 1.2      | 20    | 160    | 99.0  | 26      | 25     | 1.0      | 32    | 120    | 99.75 |
| 13      | 20     | 0.8      | 44    | 160    | 99.0  | 27      | 25     | 1.0      | 32    | 120    | 98.0  |
| 14      | 30     | 0.8      | 44    | 160    | 99.0  |         |         |          |      |        |       |

Table 2. Comparison between experimental and predicted values.

| Test1 | η (%) | Test2 | η (%) | Predicted values |
|-------|-------|-------|-------|------------------|
| 25    | 97.6  | 25    | 97.6  | Low | 98.12  | 98.53 |
| 15    | 98.0  | 15    | 99.9  | High | 99.53  | 100   |
| 40    | 98.9  | 40    | 99.3  | Low | 99.01  | 99.56 |

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