Scientia Iranica D (2012) 19 (6), 1861–1864

SCIENTIA IRANICA

Sharif University of Technology

Scientia Iranica

Transactions D: Computer Science & Engineering and Electrical Engineering

www.sciencedirect.com

Research note

Optimisation of one stage electrostatic precipitator for welding fume filtration

S.-M. Remaoun [a], A. Tilmatine [a,*], N. Hammadi [a], F. Miloua [a], K. Medles [b]

[a] APELEC Laboratory, Djillali Liabes University of Sidi Bel-Abbes, 22000, Algeria
[b] IRECOM Laboratory, Djillali Liabes University of Sidi Bel-Abbes, 22000, Algeria

Received 4 February 2012; revised 24 May 2012; accepted 14 July 2012

KEYWORDS
Electrostatic precipitator;
Corona discharge;
Designs of experiments;
Optimization;
High voltage.

Abstract In addition to huge installations of electrostatic precipitators (ESP), as those employed for dust filtration in blast furnaces and cement factories, there are also small devices as the ones used for fume filtration in welding shops. The aim of this paper is to optimize the geometric characteristics and the electric operating conditions of a "one-stage" precipitator intended for the filtration of welding fumes. The experimental bench is composed of 2 units, each consisting in an horizontal wire (tungsten, diameter 0.1 mm), energized from a high-voltage supply (+15 kV, 5 mA), and equally distant from two vertical plate electrodes (aluminium, length 200 mm × variable width) connected to the ground. Two "one-factor-at-a-time" experiments paved the way for a composite experimental design that enabled the optimization of ESP geometry, i.e. the inter-electrode interval and width of the collecting electrodes.

1. Introduction

Electrostatic precipitators are used to eliminate the solid particles (such as dust and ashes) or liquids (oil mist for example) contained in gases exiting from industries and injected into our environment [1,2]. In addition to the huge electrostatic precipitators that filter the flue gases of foundries, cement plants or thermal power stations, many other smaller-size units are developed and used for the treatment of ambient air in offices, workshops, hospitals, at very low electric energy consumption and high filtration efficiency (up to 99.9%) [3–6]. The objective of this work is to achieve the optimal design of an electrostatic filter for welding fumes, determining the optimal values of the gap between electrodes and the size of the collecting electrodes. Furthermore, we aim to achieve an optimal design using a small unobtrusive HV supply of a dozen kilovolts.

2. Design of electrostatic precipitation experiments

The *Response Surface Methodology (RSM)* can be defined as a statistical method that uses quantitative data from appropriate experiments to determine and simultaneously solve multivariable equations. RSM is a collection of mathematical and statistical techniques useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [7].

The RSM techniques employed for the present work assume that the target function (the output variable) is related to the contributing factors (the input variables u_i, $i = 1 \cdots e$) by a quadratic dependency [8,9]:

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

c_i, c_{ij} and c_{jj} are the coefficients affected respectively to input variables "u_i", interactions between variables "$u_i u_j$" and square of input variables "u_i^2". They measure the expected change in response y per unit increases in u_i when the other independent variables are held constant.

* Corresponding author. Tel.: +213 559 033 530.
E-mail addresses: remaounsm_dz@yahoo.fr (S.-M. Remaoun), atilmatine@gmail.com (A. Tilmatine), hammadinac_dz@yahoo.fr (N. Hammadi), milouaf@yahoo.fr (F. Miloua), kmedles1972@yahoo.fr (K. Medles).
Peer review under responsibility of Sharif University of Technology.

ELSEVIER Production and hosting by Elsevier

1026-3098 © 2012 Sharif University of Technology. Production and hosting by Elsevier B.V. Open access under CC BY-NC-ND license.
doi:10.1016/j.scient.2012.10.016

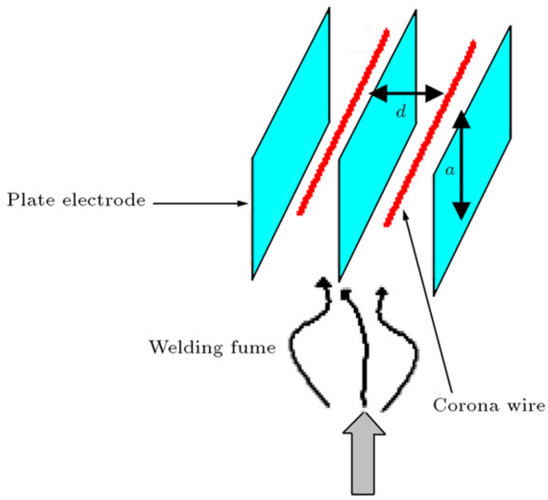

Figure 1: Schematic representation of the laboratory ESP.

Experimental designs methodology was successfully used for optimization of electrostatic processes as electrostatic separator of granular material [10]. In this paper, we aim to apply this method in order to find optimal values of geometric sizes giving maximal filtration outcome; two geometric variables were considered:

- Inter-electrodes gap (in cm);
- Width of the collecting electrode (in cm).

The screening experiments should be designed to determine the domain of variation of the two geometric factors that can be defined during the conception stage, i.e. inter-electrodes gap and the width of the collecting electrode.

The response surface modelling (RSM) techniques used in this paper assume that the response of the process is related to the different input factors.

If we assume that $+\Delta u_i$ represents the variation of the input variables and the central value is u_{i0} ($u_{i0} = u_{i\min} + \Delta u_i$), normalized centred values for the input factors can be defined as

$$x_i = (u_i - u_{i0})/\Delta u_i, \tag{2}$$

$$\text{where } u_{i0} = (u_{i\max} + u_{i\min})/2; \quad \Delta u_i = (u_{i\max} - u_{i\min})/2. \tag{3}$$

Considering these new variables, the response function becomes:

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

3. Material and method

The tests were performed on a laboratory electrostatic precipitator, configured as in Figure 1. The experimental bench is composed of 2 units, each consisting of a horizontal wire (tungsten, diameter 0.1 mm), energized from a high-voltage supply (+15 kV, 5 mA), and equally distant from two vertical plate electrodes (aluminium, length 200 mm × variable width a) connected to the ground.

The high voltage is delivered by a reversible custom-build high voltage Direct Current supply ($U_{\max} = 15$ kV, $I_{\max} = 5$ mA), using a HV transformer (Siemens 14 kV, 20 mA) energized with a Greinacher voltage doubler as shown in Figure 2. Since the objective of this work is to achieve an optimal design with a small HV power supply, we opted for all experiments for an applied voltage of 10 kV. A multimeter (FLUKE 867B, $U_{\max} = 1000$ V) and a resistive divider built in the power supply, are used to measure the applied high voltage. Figure 3 represents photography of the global experimental bench.

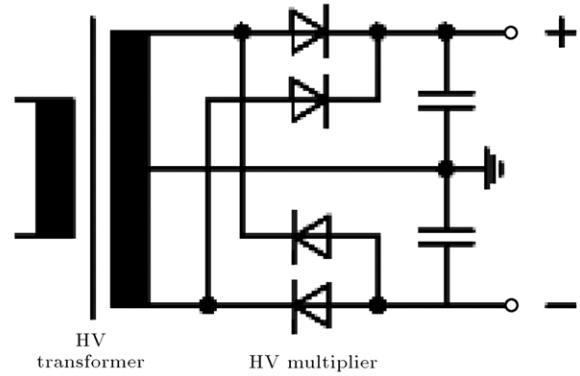

Figure 2: HV power supply circuit using Greinacher voltage doubler.

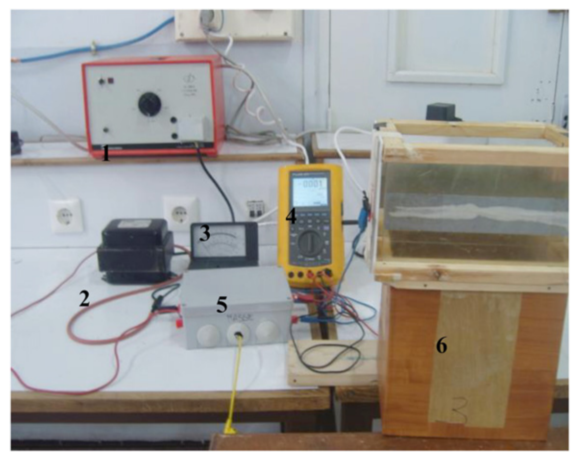

Figure 3: Experimental bench of electrostatic filtration. 1: variac; 2: HV transformer; 3 and 4: multimeters; 5: HV multiplier; 6: ESP.

Welding fume was simulated by the smoke of incense sticks. In each test, five identical sticks were burnt for a period of 5 min. The fume collected on each of the three electrodes was measured; the mass of these collecting electrodes was measured before and after each filtration experiment, using a digital balance (resolution: 0.1 mg). Each experiment was performed twice, and the mean value of the total mass collected by the electrodes was considered to be the representative for the outcome of the process.

4. Preliminary experiments

The choice of the central values and the variation intervals of the input variables was guided by preliminary experiments, called "one-experiment-at-a-time". Preliminary experiments were carried out by fixing the inter-electrodes distance to a determined value d ($d = 2, 3, 5$ and 4 cm) and by varying the width of the collecting electrode e ($e = 2, 4, 6, 8$ cm or 10 cm). The number of experiments is thus equal to $4 \times 5 = 20$. The results obtained are shown in Table 1 and illustrated using histograms in Figures 4 and 5. The total mass/d represents the sum of mass recovered in the collecting electrodes, corresponding

Table 1: Masses [g] of the collected fume for several "one-factor-at-a-time" experiments.

Width a (cm)	Inter-electrodes gap d (cm)				Total mass/a
	2	3	4	5	
2	35.2	29.6	31.2	36.3	132.3
4	37.3	38.5	31.2	32.2	139.2
6	36.7	53.0	42.8	42.6	175.1
8	36.9	47.0	43.7	30.1	157.7
10	44.5	56.2	42.9	35.5	179.1
Total mass/d	190.6	224.3	191.8	176.7	

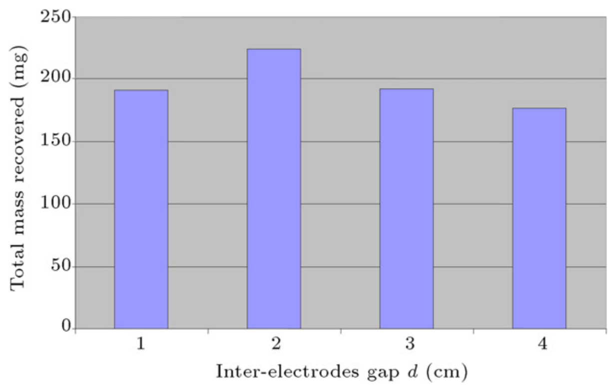

Figure 4: Total mass recovered according to inter-electrodes gap ($d = 2, 3, 4$ and 5 cm).

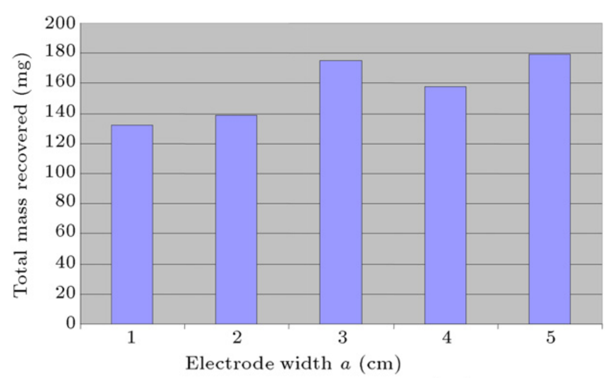

Figure 5: Total mass recovered according to width a ($a = 2, 4, 6, 8$ and 10 cm).

to a determined value of the inter-electrodes distance d and $a = 2, 4, 6, 8$ and 10 cm. The total mass/a represents the sum of mass recovered in the collecting electrodes, corresponding to a determined value of width a and $d = 2, 3, 4$ and 5 cm.

At $d = 2$ cm, the corona is intense and electric wind is such that it severely disrupts the collection of smoke. Based on this observation and the experimental data represented in Figure 4, the limits of variation of the inter-electrode gap d were fixed as $d_{min} = 3$ cm and $d_{max} = 5$ cm. Electrodes with larger width a collect larger masses of smoke, as shown in Figure 5. Therefore, the domain of variation of a was established as follows: $a_{min} = 6$ cm and $a_{max} = 10$ cm.

5. Composite designs

It is important to choose the most influent factors that are relevant to the process under study, and to define their variation interval and the appropriate central value.

Table 2: Double CCF experimental design.

Exp. N°	d [cm]	a [cm]	Mass [mg]	Exp. N°	d [cm]	a [cm]	Mass [mg]
1	3	6	47.1	12	3	6	42.1
2	5	6	38.0	13	5	6	40.0
3	3	10	53.2	14	3	10	59.3
4	5	10	38.4	15	5	10	40.5
5	3	80	45.0	16	3	8	50.0
6	5	8	35.0	17	5	8	36.0
7	4	6	46.0	18	4	6	41.4
8	4	10	47.0	19	4	10	49.0
9	4	8	41.9	20	4	8	42.0
10	4	8	43.7	21	4	8	40.4
11	4	8	41.8	22	4	8	42.0

The conclusions of the preliminary experiments served for establishing the conditions of a double central composite experimental design. This latter comprises 2×11 experiments. The results obtained for this experiment are given in Table 2.

We used software MODDE 5.0 (Umetrics AB, Umea, Sweden), which is a Windows program for the creation and evaluation of experimental designs [11]. 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 R^2. This is a measure of how well the model will predict the responses for new experimental condition. It varies between 0 and 1, where 1 indicates a perfect model and 0 no model at all.

(2) The goodness of fit parameter given by Q^2.

A good mathematical model must have criteria R^2 and Q^2 with the numerical value closes to the unit. Like R^2, Q^2 has the upper bound 1, but its lower limit is minus infinity. For a model to pass the diagnostic test, both parameters should be high, and preferably not separated by more than 0.2–0.3.

5.1. Modeling and optimization of the filtration process

The mathematical model of mass m ($R^2 = 0.89$; $Q^2 = 0.77$) was obtained with the data in Table 2:

$$m = 42.1 - 5.73d^* + 2.73a^* - 0.76d^{*2} + 3.59a^{*2} - 2.8a^*d^*. \quad (5)$$

Coefficients of the mathematical model could also be plotted as in Figure 6.

The two statistical criteria computed by MODDE 5.0 were quite satisfactory (i.e., close to unity) for both models: the goodness of fit $R^2 = 0.89$; the goodness of prediction $Q^2 = 0.77$. The predicted mass of smoke is represented in Figure 7.

The coefficients of the proposed mathematical model represent the degree of influence of all factors and interactions between them. Therefore, a high value of the coefficient means that the factor which affects the coefficient is significant, and vice versa. The inter-electrode gap d has the most important effect on the mass collected, the corresponding coefficient in the regression model being -5.73. The increase of d, which is accompanied by a diminution of the corona current, causes a decrease of the mass m. Larger quantities of m are collected at higher electrode

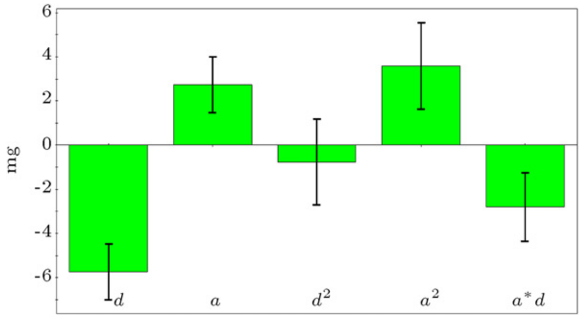

Figure 6: Plotted coefficients of the model.

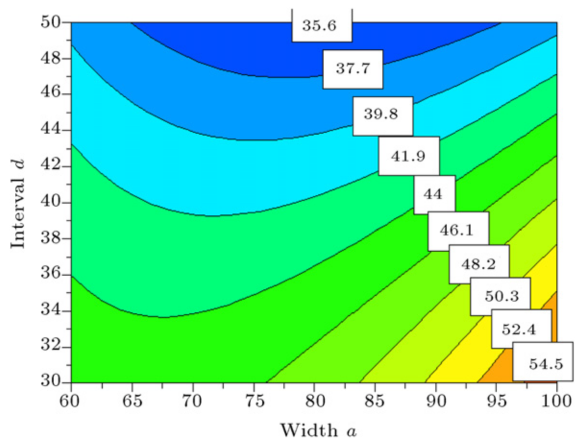

Figure 7: Contour plots of the response function computed with MODDE.

width *a*. A strong interaction exists between *a* and *d*: the effect of a change in *a* is stronger at larger *d*.

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 $d = 3$ cm and $a = 10$ cm.

6. Conclusion

An experimental study of electrostatic precipitation of welding fume was presented in this paper with the aim of achieving an optimal design of the geometric dimensions and factors such as electrode spacing and width of collection electrode which are of great importance. We build up an experimental bench of electrostatic filtration and a HV power supply. Using the method of experimental designs has resulted in the optimum sizes of the filter. Finally, we have to continue this work for examining the optimization of the electrical factors for more effective filtration; the factors to be considered are the voltage and current of the corona discharge; the final objective is to build up an ESP for industrial air filtration of welding fumes.

References

[1] White, H.J., *Industrial Electrostatic Precipitation*, Addition-Wesley, MA (1963).
[2] Parker, K.R., *Electrostatic Precipitation*, Chapman & Hall, London, UK 25–86 (1997).
[3] Oglesby, S. and Nichols, G.B., *Electrostatic Precipitation*, Marcel Dekker, New York (1978).
[4] Yagyu, T., Tsuchiya, Y., Onishi, S. and Katayama, H. "Recent electrostatic precipitation technology", *J. Mitsubishi-Juko-Giho*, 35(1), pp. 70–73 (1996).
[5] Masuda, S. and Hosokawa, S. "Electrostatic precipitation", In *Handbook of Electrostatic Processes*, J.S. Chang, A.J. Kelly and J.M. Crowley, Eds., pp. 441–480, Marcel Dekker, New York (Chapter 21) (1995).
[6] Hoenig, S.A. "New application of electrostatic technology to control of dust, fumes, smokes and aerosols", *IEEE Trans. Ind. Appl.*, IA-17, pp. 386–391 (1981).
[7] Montgomery, D.C., *Design and Analysis of Experiments: Response Surface Method and Designs*, John Wiley and Sons, Inc., New Jersey (2005).
[8] Eriksson, L., Johansson, E., Kettaneh, W.N., Wikström, C. and Wold, S., *Design of Experiments, Principles and Applications*, Learnways, Stockholm, Sweden (2000).
[9] Mori, T., *The New Experimental Design, Taguchi's Approach to Quality Engineering*, American Supplier Inst., Dearborn, MI (1993).
[10] Medles, K., Tilmatine, A., Miloua, F., Bendaoud, A., Younes, M., Rahli, M. and Dascalescu, L. "Set point identification and robustness testing of electrostatic separation processes", *IEEE Trans. Ind. Appl.*, 43, pp. 618–626 (2007).
[11] MODDE 5.0 "User Guide and Tutorial", Umetrics AB, Umea, Sweden (1999).

Sidi-Mohamed Remaoun was born in Oran, Algeria, in 1965. He received B.S. and M.S. (Dr. Eng.) degrees in Electrical Engineering from the University of Science and Technology, Oran, Algeria, in 1989 and 1993, respectively. He is currently Assistant Professor of Electrical Engineering, and member of the Electrostatics and High-Voltage Engineering Research Unit of APELEC Laboratory, at the University "Djillali Liabes" of Sidi-Bel-Abbes. His current research interests include high-voltage engineering and applied electrostatics.

Amar Tilmatine received B.S. and M.S. degrees (Dr. Eng.) in Electrical Engineering from the University of Science and Technology, Oran, Algeria, in 1988 and 1991, respectively. He obtained a Ph.D. degree in 2004 from the Electrical Engineering Institute of Sidi-Bel-Abbes University, Algeria, and, in 2010, he was promoted to the rank of Professor. Since 1991, he has been teaching electric field theory and high-voltage engineering at the Institute of Electrical Engineering, University of Sidi-Bel-Abbes, Algeria. He was Chairman of the Scientific Committee of this Institute from November 2002–2005. He is also Head of the research group "Electrostatics and High-Voltage Engineering" of IRECOM Laboratory. At least once a year, from 2001 to 2009, he has visited the Electronics and Electrostatics Research Unit of the University Institute of Technology, Angoulême, France, as an Invited Scientist, to work on a joint research project on new electrostatic separation technologies. His other fields of interest are high-voltage insulation and gas discharges. He has been a senior member of IEEE since 2009. He is Director of APELEC Laboratory since May 2012.

Nacera Hammadi was born in Tlemcen, Algeria, in 1967. She received a B.S. degree in Electrical Engineering from the University of Science and Technology, Oran, Algeria, in 1989, and a M.S. (Dr. Eng.) degree in 1999. She has been working towards her Ph.D. degree at the Institute of Sidi-Bel-Abbes University, Algeria since 2009; she has also been working as Professor in the Electrical Engineering Department at the University of Science and Technology, Oran, Algeria since 2000, and is a member of the APELEC Laboratory. Her current research interests are high voltage engineering and gas discharges.

Farid Miloua was born in 18 September1974 and received his M.S. degree in electrical engineering and the Magister (Dr. Eng.) degree from the Faculty of Engineering in University Dillali Liabes, Sidi-Bel-Abbes, Algeria, in 1998 and 2004, respectively. He has been teaching electric field theory and high-voltage techniques at the Institute of Electrical Engineering, University of Bechar, Algeria since 2004. He is now teaching at university of Sidi-Bel-Abbes in Algeria, where he is also a member of the research group "Electrostatics and High-Voltage Engineering" APELEC Laboratory. His principal field of research is about electrostatic applications, as electrostatic separation and precipitation. His other fields of interest are high-voltage insulation and gas discharges.

Karim Medles was born in Tipaza, Algeria, in 1972. He received B.S. and M.S. degrees (Dr. Eng.) in Electrical Engineering from the University of Sidi Bel-Abbes, Algeria, in 1994 and 1999, respectively. He joined the University of Sidi Bel Abbes, Algeria in 1999 as Senior Lecturer at the Institute of Electrical Engineering where he is currently Assistant Professor. He obtained his Ph.D. degree in 2006 from the Electrical Engineering Institute, University of Sidi Bel-Abbes, Algeria, with a thesis he partly prepared at the University Institute of Technology, Angoulême, France, with an 18-month research scholarship awarded by the French Government. He is Head of the "Electrostatics and Methodology" Research Unit of IRECOM Laboratory at the University of Sidi-Bel-Abbes, Algeria. He has published several scientific papers in international and national journals, as well as in conference proceedings. He was invited as visiting scientist to France. His current research interests include: power systems, high-voltage engineering and electrostatics. Nowadays, his principal research activities concern triboelectric separators and charging devices.