Fine particle capture performance assessment in an electrostatic-fabric integrated precipitator

Avaliação do desempenho da captura de partículas finas em um precipitador integrado de tecido eletrostático

DOI: 10.54021/seesv5n1-113

Recebimento dos originais: 26/04/2024
Aceitação para publicação: 17/05/2024

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ABSTRACT
Electrostatic precipitators, which are more commonly referred to as precipitators, play a crucial role in the process of reducing the quantity of airborne contaminants that are present in both atmospheric and flue gas settings. This is because precipitators are able to lower the concentration of contaminants in the air. The fine particles, ash, and oil that make up these pollutants are included. With a special emphasis on a Cottrell-type electro-filter that makes use of the wire-cylinder arrangement, the goals of this study are to evaluate the practicability of various filtration systems for the purpose of air decontamination. Specifically, the study will focus on the Cottrell-type electro-filter. By conducting a thorough examination of the peculiarities of the electrical and physical parameters that regulate the mechanisms of particle aggregation, our major purpose is to achieve a
comprehensive understanding of these parameters. Through the use of experimental design strategies, we will make an effort to construct and perfect the filtration process in the subsequent stage. In addition to that, the purpose of this inquiry is to explore the impact that high voltage levels and the diameter of the conductor wire that is incorporated into the prototype have. Especially notable is the fact that our prototype exhibits an incredible filtration efficiency, with rates reaching up to 98%. This performance is really remarkable. Its exceptional performance reveals that it has the potential to be suitable for a wide variety of contexts, including residential, commercial, healthcare, industrial, and workshop applications. This suggests that it has the potential to be suitable for a wide range of applications.

**Keywords:** electrostatic-filter precipitator, air pollution control, new dust removal technology, fine particle capture, electrostatic precipitation ECP.

**RESUMO**
Os precipitadores eletrostáticos, mais comumente chamados de precipitadores, desempenham um papel fundamental no processo de redução da quantidade de contaminantes transportados pelo ar que estão presentes nas configurações atmosféricas e de gás de combustão. Isso ocorre porque os precipitadores são capazes de diminuir a concentração de contaminantes no ar. As partículas finas, as cinzas e o óleo que compõem esses poluentes estão incluídos. Com ênfase especial em um eletrofiltro do tipo Cottrell que faz uso do arranjo de cilindro de arame, os objetivos deste estudo são avaliar a praticidade de vários sistemas de filtragem para fins de descontaminação do ar. Especificamente, o estudo se concentrará no eletrofiltro do tipo Cottrell. Ao realizar um exame minucioso das peculiaridades dos parâmetros elétricos e físicos que regulam os mecanismos de agregação de partículas, nosso principal objetivo é obter uma compreensão abrangente desses parâmetros. Com o uso de estratégias de projeto experimental, faremos um esforço para construir e aperfeiçoar o processo de filtragem no estágio subsequente. Além disso, o objetivo desta pesquisa é explorar o impacto dos níveis de alta tensão e do diâmetro do fio condutor incorporado ao protótipo. Especialmente notável é o fato de que nosso protótipo apresenta uma incrível eficiência de filtragem, com taxas que chegam a 98%. Esse desempenho é realmente notável. Seu desempenho excepcional revela que ele tem o potencial de ser adequado a uma ampla variedade de contextos, incluindo aplicações residenciais, comerciais, de saúde, industriais e em oficinas. Isso sugere que ele tem o potencial de ser adequado para uma ampla gama de aplicações.

**Palavras-chave:** precipitador de filtro eletrostático, controle de poluição do ar, nova tecnologia de remoção de poeira, captura de partículas finas, precipitação eletrostática ECP.
1 INTRODUCTION

In recent years, the global environment has faced significant challenges arising from both anthropogenic and natural sources. These challenges manifest in the form of increased airborne particulate matter and alterations in atmospheric chemical composition. Consequently, these issues have had multifaceted consequences, influencing not only air quality but also posing risks to ecosystems, wildlife, and public health infrastructure. Furthermore, these environmental changes have led to reduced visibility and the generation of unpleasant odors.

These considerations underscore the imperative for concerted efforts to mitigate emissions of gaseous pollutants and enhance air quality.

One technology that has emerged as a robust solution for addressing the aforementioned challenges is electrostatic filtration. Electrostatic filters are widely employed in industrial settings to efficiently remove airborne particulate matter carried by smoke and dust [1-4]. Their longevity makes them an economically viable option, with applications spanning various industries, including environmental protection. Recent developments have also extended their utility to indoor air purification [5-8].

Among the earliest applications of electrostatic filtration is electrostatic dust removal, commonly known as the electrostatic precipitator, electro-filter, or electrostatic dust collector. This process has demonstrated remarkable efficiency in separating particles from gases and is predominantly employed in heavy industries such as steel manufacturing, waste incineration, cement production, and power generation [1-4].

Additionally, it finds utility in domestic settings, effectively cleansing indoor air in spaces plagued by tobacco smoke and in occupational environments where pollutants like wood dust, cement, and flour are prevalent. Notably, electrostatic precipitators exhibit exceptional efficacy, particularly in capturing micron and submicron particles, where alternative systems often falter.

This study introduces an experimental apparatus that serves as a platform for characterizing a cylindrical electrostatic precipitator of the Cottrell type [9]. This specific electrostatic filter is employed in environments laden with dust particles originating from various materials; including cement, flour, and wood mulch [10-11].

The efficiency of electrostatic precipitators is influenced by a multitude of factors, encompassing electrical, geometrical, and physicochemical parameters.
While the individual effects of these factors are known, understanding their interplay remains a challenge. For instance, when both high voltage and airflow vary simultaneously, the dominant influence remains uncertain.

To address such complexities, we employ the Design of Experiment (DOE) methodology, a potent tool for modeling and analyzing interactions among these factors [14]. Through DOE, we seek to develop a mathematical model that elucidates the relationships between the selected factors [15].

The findings of this research endeavor are poised to stimulate further exploration in the development of advanced models for electrostatic precipitators. This is particularly relevant considering the simplicity of their operational principle and their minimal equipment requirements, offering promising avenues for continued innovation in this critical realm of environmental protection.

The objective of this work is to conduct an in-depth examination of the electrical and physical parameters governing particle aggregation mechanisms in an electrostatic-fabric integrated precipitator. The researchers seek to devise and optimize the filtration process employing experimental design methodologies, with a particular focus on investigating the influence of high voltage levels and the diameter of the conductor wire integrated into the prototype. The ultimate goal is to develop a comprehensive mathematical model that elucidates the relationships between the selected factors to further the understanding and optimization of electrostatic precipitators.

2 MATERIALS AND METHODS

In pursuit of our primary research objective, we adopted a straightforward approach, anchored in two pivotal facets of our methodology: the screening technique and the response surface methodology.

The screening technique serves as a valuable tool for navigating uncharted empirical domains, while the response surface method empowers us to construct comprehensive descriptive or predictive models of the phenomena under investigation.

Our experimental setup is endowed with an array of diverse instruments and apparatuses, facilitating the deliberate manipulation of key parameters governing filter performance, including the measurement of principal characteristic
dimensions. This experimental framework comprises three distinct components, as illustrated in Figure 1:

![Experimental device descriptive Diagram of the laboratory](image)

These components collectively form the foundation upon which our investigation is built, allowing for systematic exploration and in-depth analysis of the intricate dynamics within the domain of electrostatic filtration.

3 PRINCIPAL AIR CIRCUIT

The principal air circuit is comprised of a blower that draws in ambient air and propels it into the system.

4 AIR-PARTICLE MIXTURE (TANK)

Within this tank, the contaminated substance is housed, strategically positioned upstream of a blower. The blower serves the dual purpose of introducing the polluted air into the system and expelling it towards the chimney of the electrostatic precipitator, which is a cylindrical metal structure.

5 CHIMNEY

The chimney is constructed as a metallic cylinder with a diameter (D) of 80 millimeters and a length (L) of 500 millimeters. It is firmly connected to the ground. The emissive electrode at the core of the chimney is a central copper wire, boasting a diameter (d) of 0.7 millimeters. This electrode is linked to a continuous high-voltage source, positively polarized, which a high-tension generator (HT) supplies.
5.1 EXPERIMENTAL PROCEDURE

In the fundamental operation of the simplest electrostatic filters, known as concentric Wire-Cylinder filters, a significantly elevated electric potential is applied to a wire, referred to as the transmitting electrode. This wire is positioned coaxially within a vertical cylinder, termed the collecting electrode, which is grounded. The gas containing the particles to be eliminated is introduced through an inlet located at the base of the cylinder.

As the gas permeates the inter-electrode space [16], the corona effect comes into play, leading to the ionization of the gas surrounding the wire. This ionization process generates ions and electrons [17-21].

Subsequently, these ions and electrons interact with the contaminated particles present in the gas stream. The particles acquire an electrical charge through this interaction and are consequently attracted toward the internal surface of the cylinder under the influence of the electric field. The charged particles then adhere to the inner surface of the cylinder, and their removal is achieved through methods such as washing, scraping, or mechanical agitation.

These collected particles are accumulated within hoppers and ultimately evacuated from the electrostatic precipitator through a discharge system. It is worth noting that a growing number of researchers have undertaken studies in the realm of electrostatic precipitation, often employing numerical simulations to enhance our understanding of these complex processes [22].

5.2 CURRENT & VOLTAGE CHARACTERISTIC

5.2.1 Diameter influence of the wire

In our experimental procedure, we apply a steadily increasing positive electric potential to the wire. During this process, we carefully monitor and measure the electric current flowing onto the cylinder.

This procedure is repeated until the electric potential approaches the breakdown voltage threshold. Importantly, we conduct this experiment using two distinct diameters of copper wire, as illustrated in Figure 2.
The observed inverse proportionality between the diameter of the yarn and the electric discharge is entirely expected. This relationship aligns with physical principles since the electric field intensity around the wire is inversely proportional to the wire’s radius $R_0$. As the wire diameter decreases, the electric field strength increases, leading to more pronounced electric discharges.

\[ E = \frac{q}{4\pi\varepsilon R_0} \]  

Where:

- $E$, represents the electric voltage at a point in space.
- $q$, represents the electric charge.
- $\varepsilon$, represents the permittivity of the material used.
- $R_0$, represents the distance from the point of interest to the location of the charge.

### 5.2.2 Diameter influence of the cylinder

We follow a similar approach as in the previous phase, this time considering two different cylinder diameters. With a constant corona wire diameter of 0.7 millimeters (mm), we chart the characteristic voltage for cylinder diameters of 80 and 110 millimeters (mm), as depicted in Figure 3.
Figure 3. Voltage characteristics for two different diameters of the cylinder

![Voltage characteristics for two different diameters of the cylinder](image)

Once again, the reduction in electric discharge with an increase in the diameter of the induced cylinder can be explained through the linear current relation proposed by Townsend's law.

This law suggests that the current is directly proportional to the applied voltage and inversely proportional to the distance between the electrodes, which, in this case, is influenced by the cylinder diameter. Therefore, as the cylinder diameter increases, the distance between the electrodes also increases, resulting in a reduction in electric discharge, in line with Townsend's law.

\[
I_{\text{linear}} = \frac{8\pi \mu_{\text{ion}} \varepsilon_0}{R^2 \ln \left( \frac{R}{R_0} \right)} V (V - V_0) \quad (2)
\]

\[
V_0 = E_0 R_0 \ln \left( \frac{R}{R_0} \right) \quad (3)
\]

Where:

- \( \mu_{\text{ion}} \): electrical mobility of ions in the drift zone (m².V⁻¹.s⁻¹).
- \( \varepsilon_0 \): vacuum dielectric constant (F.m⁻¹).
- \( V \): potential difference in the inter-electrode space (V).
- \( V_0 \): difference in potential for the appearance of the corona effect (V).
- \( E_0 \): disruption gradient (V.m⁻¹).
- \( R_0 \): represents the distance from the point of interest to the location of the charge (m).
- \( R \): The radius of the cylinder (m).
6 RESULTS AND DISCUSSION

6.1 EXPERIMENTS OPTIMIZATION DESIGN

The design of experiments is an indispensable tool in the toolkit of any researcher, as it serves to optimize the organization of experiments. Its primary goal is to maximize the acquisition of information while minimizing the number of experiments required. Additionally, it enhances the precision of result modelling and, subsequently, process optimization [23-27].

Coefficients necessary for the model can be computed or estimated through data processing software. Interpreting the model necessitates evaluating the relative significance of each coefficient and determining the quadratic dependencies established between the factors and the response variable.

In our investigation, we focused on two factors that exhibit a significant influence on filtration effectiveness: the applied high voltage, denoted as $U(kV)$, and the airflow, denoted as $D_e(V)$. The relationship between the blower’s airflow and voltage is expressed as follows:

$$D_e = kU$$

Where:

$D_e$, Airflow delivered by the blower.
$U$, Voltage (V).
$k$, Proportionality factor.

In our experimental study, we employ this voltage as an indicator of airflow expressed in volts.

For accurate predictions, it is important to note that the study results are valid only within the specified range of factor variations, as outlined in Table 1:

<table>
<thead>
<tr>
<th>Factor</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>High voltage $U (kV)$</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>Flow $D_e (V)$</td>
<td>150</td>
<td>220</td>
</tr>
</tbody>
</table>

Source: Authors

In our study, we selected a single response variable, which is the filter output or yield. The following formula calculates the yield:
\[ \eta_\% = \frac{m_c}{m_i} \times 100 \] (5)

Where:

\( \eta_\% \), yield (%)

\( m_c \), Mass recovered in the drawer after cleaning the filter chimney.

\( m_i \), Total mass introduced into the precipitator during the test.

Figure 4. The realised electrostatic filter Photography

Source: Authors

6.2 MAIN EFFECTS PLOT OF FACTORS

It is readily apparent that alterations between the low and high levels of factors have a varying degree of influence on the response variation, depending on the specific factors under consideration.
Figure 5 illustrates that voltage stands out as the most influential factor in the response. This conclusion is drawn based on the efficiency value, which corresponds to the most significant mass variation concerning the center of the interval. This representation visually conveys the interplay and relationships between the effects of the various factors, helping to discern their relative importance in influencing the response.

### 6.3 COUPLINGS FACTORS EFFECTS

Interactions are termed "couplings" when they specifically pertain to assessing the influence of one factor in relation to another, without involving additional elements. In mathematical terms, these are classified as first-order interactions. To aid in comprehending the outcomes of the design of experiments, interactions can be visually represented on a graph, simplifying their interpretation, as illustrated in Figure 6.
Figure 6. Graph of the interaction between the two factors studied

6.4 STUDIED SYSTEM MODEL

The postulated mathematical model used by the composite plans is a model of the second degree with interactions. We preserved, in general, only the interactions of order two. For a model with two elements, the answer can be expressed by:

\[ y = \beta_0 + \sum_{i=1}^{k} \beta_i \bar{X}_i + \sum_{i=1}^{k} \beta_{ii} \bar{X}_i^2 + \sum_{j=i+1}^{k} \beta_{ij} \bar{X}_i \bar{X}_j + \varepsilon \]  \hspace{1cm} (6)

Where:

(\(\beta, \beta_i, \beta_{ij}\)), the effect coefficients.

(\(\bar{X}\)), the reduced centered values of the factors.

The full tests number \(N\) will depend on the factors number \(K\) studied and on the repetitions number in the center of the field, \(n_0\):
\[ N = n_f + n_\alpha + n_0 \]  \hspace{1cm} (7)

Where:

- \( n_f \), many tests of the complete factorial design.
- \( n_\alpha \), a test number of the plan out of \( n_\alpha = 2k \).
- \( n_0 \): a test number in the centre of the studies field, according to the experimenter's choice.

Hence, the total number to be carried out for \( K = 2 \) and \( n_0 = 3 \) is 11 quite precise tests? In each trial, we used 25 (g) of the product (cement particles) of diameter lower than 80 (µm). All the tests were conducted under the same climatic conditions; the temperature and moisture were from 17 to 22°C and 52% to 60%, respectively.

The factor levels for each experimental point as well as the results of the tests are gathered in Table 2.

Table 2. Tests results of the composite plan with two factors

<table>
<thead>
<tr>
<th>N° Tests</th>
<th>U (kv)</th>
<th>De (v)</th>
<th>( \eta ) cement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
<td>150</td>
<td>84</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>150</td>
<td>98</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>220</td>
<td>86</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>220</td>
<td>96</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>185</td>
<td>84,8</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>185</td>
<td>96,4</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>150</td>
<td>93,2</td>
</tr>
<tr>
<td>8</td>
<td>19</td>
<td>220</td>
<td>94,4</td>
</tr>
<tr>
<td>9</td>
<td>19</td>
<td>185</td>
<td>95,2</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>185</td>
<td>95,6</td>
</tr>
<tr>
<td>11</td>
<td>19</td>
<td>185</td>
<td>96</td>
</tr>
</tbody>
</table>

Source: Authors

This computer tool plays a crucial role in automating and expediting the process of determining the optimal conditions for achieving products that meet specific quality standards. To achieve this, we employed the advanced software, MODDE 9.0.
MODDE stands as a cutting-edge design of experiments software package, widely utilized by scientists, engineers, and statisticians alike. Its purpose is to facilitate a deep understanding of intricate processes and products [30], [31], [32], [33].

Upon computing various effect coefficients, we derived the following mathematical model:

\[
\eta\% = 95.14 + 5.94 \bar{U} + 0.20 \bar{D}_e - 3.84 \bar{U}^2 - 0.64 \bar{D}_e^2 - \bar{U} \bar{D}_e \tag{9}
\]

As well as:

\[\bar{U} \& \bar{D}_e,\] the reduced centered values of the high voltage and the airflow respectively.

The figure below depicts the effect coefficients of the mathematical model alongside their respective confidence intervals. Each coefficient value signifies the change in the response when one factor is varied from zero to one in coded units, while keeping the other factors at their mean values. Significance of a coefficient, indicating it is distinct from random noise, is affirmed when the confidence interval does not intersect with zero.

![Figure 7. Values of effect coefficients and factor interactions](image)

Figure 8 unmistakably illustrates the significant impact of high voltage on filtration yield. Within the selected airflow interval of [150; 220], the yield reaches an impressive 96%. However, this level of performance is attainable only when the voltage is set at or above 20 kilovolts (kV).
This phenomenon can be attributed to the influence of high voltage on the ionization of cement particles, resulting in an augmentation of the electric field within the cylinder.

In this study, high voltage emerges as the predominant and most influential factor affecting filtration effectiveness.

Figure 8. Yield surface answer according to the high voltage and the flow.

6.5 STUDIED SYSTEM MODEL

The physicochemical characteristics of gas-induced pollution products stand as pivotal factors demanding thorough investigation to optimize the efficiency of electrostatic filtration. Filtration experiments have been conducted on two distinct products, namely "flour" and "cement," both characterized by relatively similar granulo-metric sizes, with particle diameters falling below 80 micrometers (µm).

Figure 9. Physico-chemical characteristic influences of the product on the filtration effectiveness.

The disparity in filtration effectiveness observed between the two products primarily arises from the distinct chemical compositions of cement. Specifically,
industrial adhesive contains varying metal concentrations ranging between 20 and 300 milligrams per kilogram (mg/kg). This disparity in metal content poses challenges in particle adhesion to the cylinder’s surface.

Additionally, it leads to a higher occurrence of sparks during the filtration process. Furthermore, the physicochemical characteristics of the product directly influence its resistivity. Higher metal concentrations in the product result in reduced resistivity. The impact of airflow on the yield of flour is more pronounced compared to its effect on cement yield. However, it is crucial to note that high voltage remains the most influential factor in both cases. The following mathematical models substantiate these findings:

\[
\eta_{\text{flour}} \% = 97.48 + 2.2 \bar{U} + 1.42 \bar{D_e} - 1.55 \bar{U}^2 - 0.003 \bar{D_e}^2 - 1.85 \bar{U} \bar{D_e}
\] (10)

The influence of airflow on flour yield varies significantly, ranging from 97% to 99% when the voltage is in the range of 15 kV to 23 kV. Conversely, it can approximately drop to 96% at a voltage of 20 kV.

This phenomenon can be explained by the effect of airflow on flour particles, which increases the aerodynamic sweeping force towards the exterior of the filter.

Figure 10. Yield answer surfaces according to the high voltage and the airflow.
6.6 PROCESS OPTIMISATION

The factors levels of the optimal operation point of the process must belong to the factors intervals of the optimal answer surface.

The optimum of our process of filtration predicted by the postulated mathematical model is obtained by the command point according to:

\[
\begin{align*}
U_{\text{optimal}} &= 24 \, kV \\
D_e &= 150 \, V
\end{align*}
\]

This point corresponds to an output/yield of 97, 38% and 98,54% for Cement and the Flour respectively.

7 CONCLUSION

Our research underscores the efficacy of Multivariate Polynomial Expansion (MPE) alongside its statistical and experimental modeling tools in analyzing a series of tests conducted on an electrostatic precipitator. Through the application of the Response Surface Method (MSR), we have successfully identified optimal operating conditions for the produced filter.

The study yielded several noteworthy findings:
- increase in Air Conductivity with Voltage \( I = f(U) \);
• we observed a direct correlation between air conductivity and voltage, highlighting the influence of electrical potential on the filtration process.
• reduction in Air Conductivity with Cylinder Diameter. As the diameter of the cylinder increased, we noted a decrease in air conductivity, signifying the significance of geometric factors in filtration efficiency.
• reduction in Air Conductivity with Yarn Diameter. Similarly, an increase in yarn diameter led to reduced air conductivity, emphasizing the role of physical characteristics in the filtration process.
• by employing the experimental design method "MPE," we effectively modeled influential parameters in the filtration process, including the effects of high voltage, airflow rates, and physicochemical properties of the powder. The results substantiate that the electrostatic precipitator is not only feasible but also capable of achieving an impressive 98% filtration efficiency, affirming its practical effectiveness;

Finally, the result of this research can assist society and academia are:
• improve air quality and mitigate health/environmental impacts through highly efficient air filtration.
• stimulate development of advanced electrostatic precipitator models and understanding.
• provide a framework for studying complex interactions using Design of Experiment methodology;
• contribute to the broader knowledge base on particle aggregation and electrostatic precipitation.

The main limitations and recommendations for future work based on the research are:
• the study only examined one specific Cottrell-type electrostatic precipitator prototype;
• the analysis of interactions between parameters could be expanded beyond the Design of Experiment approach used.

In The end, we recommended for future work to:
• evaluate performance of other electrostatic precipitator designs and configurations;
• incorporate more recent advancements in materials, power sources, and control systems;
• develop more sophisticated mathematical models to better elucidate complex interactions;
• conduct long-term field trials to assess real-world performance and durability;
• explore scalability and cost-effectiveness for broader commercial/industrial application;
• investigate integration with other air filtration technologies for enhanced efficiency;
• overall, this research provides a solid foundation, but there remains significant potential for further optimization and expansion of electrostatic precipitator technology to address evolving air quality challenges.
REFERENCES


