RESPONSE SURFACE METHODOLOGY TO EVALUATE THE EFFECTS OF GEOMETRIC PARAMETERS ON THE ELECTROSTATIC PRECIPITATION

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1. INTRODUCTION

The high number of industrial emissions is harmful for the environment and the population health, due to the high concentration of particles. In this scenario, the electrostatic precipitator (ESP) is presented as a viable alternative in the air pollution control system, by reducing the particulate material concentration. This equipment is characterized for high collection efficiencies and low pressure drops (Wang, 2020; Bin *et al*., 2017).

The main components of the ESP are the discharge and collecting electrodes, which are negatively charged and grounded, respectively. Due to the electrode different polarities, an electric field is generated inside the ESP duct and the particles are electrically charged and collected. The electrostatic precipitation is influenced by operating conditions and geometric parameters, as observed in previous works (Zheng *et al.*, 2020; Yang *et al*., 2021). However, the influence of these parameters in the collection efficiency has not been widely discussed for nanoparticles. The studies performed in this diameter range, although achieved relevant results, presented some experimental restrictions (De Oliveira and Guerra, 2018; Li *et al*., 2019; Chen *et al,* 2020; Andrade and Guerra, 2021). Therefore, it is interest to investigate by alternative methods the behavior of the electrostatic precipitation under different conditions.

In this study, the influence of the number and diameter of the discharge electrodes on the performance of the ESP in the collection of nanoparticles, with different air velocities and electric field intensities, were evaluated through an ANOVA analysis and the response surface methodology.

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2. MATERIALS AND METHODS

2.1 Experimental Unit

The experimental unit used is composed by several equipment, as can be seen in Fig. 1. First, the inlet air enters the experimental apparatus and passes through purification filters (Model 3074B, TSI), to remove impurities, while the NaCl aerosol is generated at portable aerosol generator (Model 3079A, TSI) and mixed with the purified air. After that, the excess moisture is retained by a diffusion dryer (Model 3062, TSI) and the particles are neutralized by a Krypton-85 aerosol neutralizer (Model 3054, TSI) and enter the ESP, which is connected to a high voltage power supply (Model SL30PN300, Spellman). The phenomenon of electrostatic precipitation occurs inside the ESP duct and the particles are collected. The outlet airflow passes through a 3-way valve and is neutralized, with a source of Americium-241, to prevent imprecise results. A Scanning Mobility Particle Sizer (SMPS), composed by an electrostatic classifier (Model 3080, TSI) and an ultrafine condensation particle counter (Model 3076, TSI), operating for diameters between 5.83 and 228.8 nm, were used to determine the collection efficiency of ESP.

2.1 Operational Conditions and Statistical Analysis

The experiments were performed in a wire-plate single-stage ESP with two copper collecting plates spaced in 6.5 cm. The number of wires analyzed was 1 and 2, with the wire-spacing of 6.5 cm, for the wire diameters of 0.3 and 0.4 mm, the air velocities of 1.03 and 4.08 cm/s, and the electric fields of 3.08 and 3.38 kV/cm.

After the experiments, the overall collection efficiencies were calculated by Eq. 1.

$$\eta = \frac{C_i - C_f}{C_i} \times 100\% \qquad (1)$$

Where, η is the electrostatic precipitator efficiency (%), C_i is the inlet particle concentration (µg/m³), and C_f is the outlet particle concentration (µg/m³).

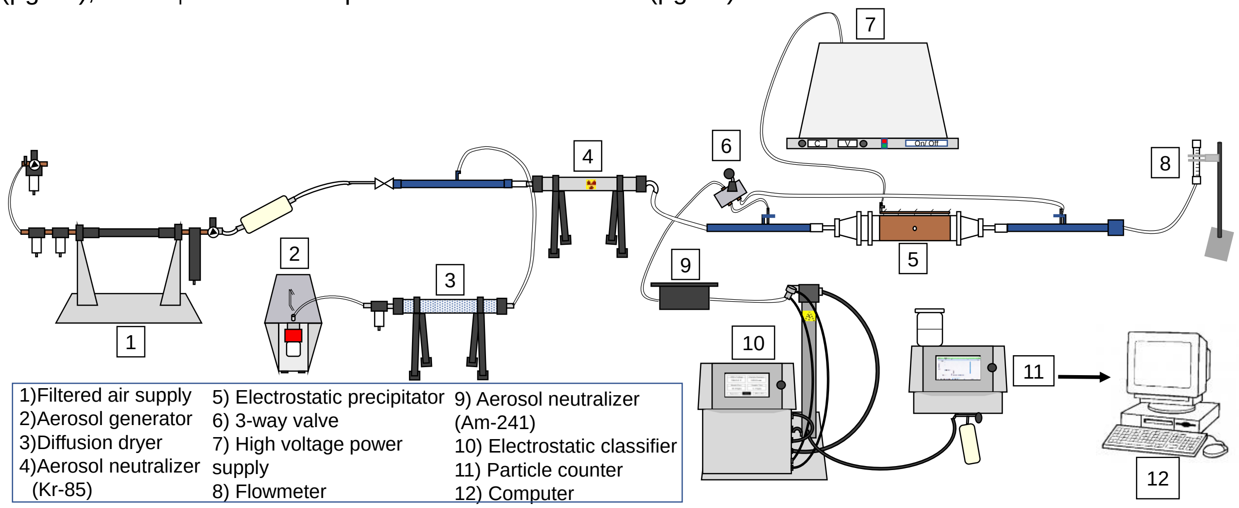

Figure 1: Representation of the experimental unit.

Adapted from Andrade and Guerra (2021).

The overall efficiencies results were applied on a statistical analysis of 2^4 factorial design (4 factors and 2 levels) to determine the parameters with the most significant effects. It was evaluated the influence of each variable on the collection efficiency through the analysis of the effects, the standard error, and the statistical significance (p-value), with a confidence interval of 95%.

Initially, was evaluated the influence of each variable on the collection efficiency, through the analysis of the effects, the standard error and the statistically significant (p-value). The effects presented a positive sign when increased the value of the response variable, in this case, the collection efficiency, and negative when reduced their value. Higher values mean greater effect.

The p-value indicates the significance of the factor on the response variable. Since the confidence interval of 95% was used in the statistical calculus, the p-value must be higher than 0.05 to be considered significant (Santos, 2014).

Then, a variance analysis (ANOVA) was performed to confirm the variables that presented a significant influence on the efficiency results, based on the p-value and the values of F, the ratio between the variance among sample means and the variance within the samples (Minitab, 2019). These influences were quantified through the Pareto chart. Moreover, the response surfaces were plotted, a methodology used to visualize the behavior of the response variable as a function of independent variables.

3. RESULTS AND DISCUSSION

Table 1 show the results of estimated effect, pure error, t value and the level of statistical significance. The lines in bold type refer to the factors considered significant for the results.

Therefore, all factors evaluated initially were significant for the particle collection efficiency, as the combined effect of some factors, due to p-values lower than 0.05.

The wire diameter and the air velocity presented a negative effect. Hence, by increasing the wire diameter from 0.3 to 0.4 mm, the efficiency reduced by 30%, while with the increase of the air velocity from 1.03 to 4.08 cm/s, the efficiency reduced in about 14%.

On the other hand, the number of wires and the electric field showed a positive effect on the efficiency results, since increasing the number of wires from 1 to 2 the efficiency was 5% higher and the increase of the electric field from 3.08 to 3.38 kV/cm, increased by 36% the collection efficiency.

The interaction among some effects was also significant, however, the interaction between the wire diameter and the electric field presented the highest influence.

The results prediction was confirmed through ANOVA (Table 2), which showed the influence of all factors evaluated. As in Table 1, The lines in bold type refer to the factors considered significant for the results.

Table 1: Estimated effect, pure error, t value and level of statistical significance.

Factor	Estimated Effect	Standard Error	t (32)	p
Average	**76.0971**	**0.140766**	**540.594**	**0.000000**
(1) Wire Diameter	**-30.8417**	**0.281531**	**-109.550**	**0.000000**
(2) Number of Wires	**4.9817**	**0.281531**	**17.695**	**0.000000**
(3) Air Velocity	**-14.1933**	**0.281531**	**-50.415**	**0.000000**
(4) Electric Field	**36.0892**	**0.281531**	**128.189**	**0.000000**
Wire Diameter and Number of Wires	**1.0958**	**0.281531**	**3.892**	**0.000473**
Wire Diameter and Air Velocity	0.3758	0.281531	1.335	0.191309
Wire Diameter and Electric Field	**28.0283**	**0.281531**	**99.557**	**0.000000**
Number of Wires and Air Velocity	**0.9492**	**0.281531**	**3.371**	**0.001968**
Number of Wires and Electric Field	0.4817	0.281531	1.711	0.096782
Air Velocity and Electric Field	**3.4233**	**0.281531**	**12.160**	**0.000000**
1*2*3	**-1.1717**	**0.281531**	**-4.162**	**0.000222**
1*2*4	-0.3158	0.281531	-1.122	0.270278
1*3*4	**-3.4225**	**0.281531**	**-12.157**	**0.000000**
2*3*4	**3.8142**	**0.281531**	**13.548**	**0.000000**

Besides that, the graph of predicted values of collection efficiency *versus* observed (Fig. 2) presented a good adjust of the model with the experimental data, with a coefficient of determination (R^2) of 0.9979. Moreover, the model showed a small value of lack of adjust.

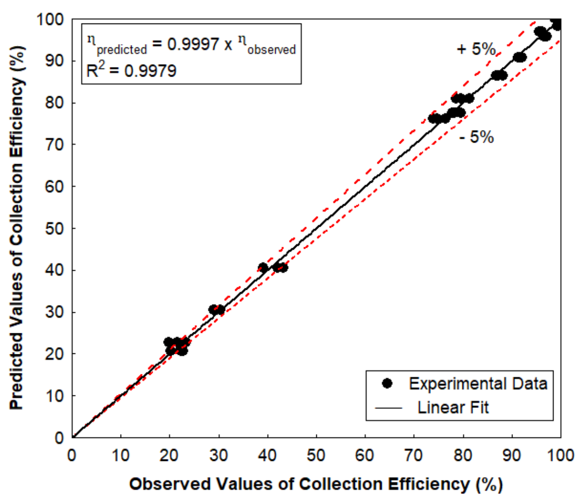

Figure 2: Predicted values of collection efficiency *versus* observed.

A Pareto chart (Fig. 3) was plotted for a better understanding of the effects more significant on the collection efficiency results. The electric field was the factor with higher influence, presenting a positive effect, which resulted in an increase of the efficiency with higher electric fields.

The second factor more significant was the wire diameter, with a negative effect, once the diameter of 0.4 mm achieved a lower efficiency when compared with the diameter of 0.3 mm.

In a similar way, the air velocity presented a negative effect. It is important to highlight that the interaction between the wire diameter and the electric field had a positive effect, because even increasing the wire diameter to 0.4 mm, with an electric field of 3.38 kV/cm, the collection efficiency increased. Moreover, the positive effect of the number of wires was observed.

Table 2: Analysis of variance of the model adjusted for particle collection efficiency

Factor	Sum of Squares	Degrees of Freedom	Square Mean	F	p
(1) Wire Diameter	**11414.50**	**1**	**11414.50**	**12001.13**	**0.000000**
(2) Number of Wires	**297.80**	**1**	**297.80**	**313.11**	**0.000000**
(3) Air Velocity	**2417.41**	**1**	**2417.41**	**2541.65**	**0.000000**
(4) Electric Field	**15629.14**	**1**	**15629.14**	**16432.37**	**0.000000**
Wire Diameter and Number of Wires	**14.41**	**1**	**14.41**	**15.15**	**0.000473**
Wire Diameter and Air Velocity	1.70	1	1.70	1.78	0.191309
Wire Diameter and Electric Field	**9427.05**	**1**	**9427.05**	**9911.54**	**0.000000**
Number of Wires and Air Velocity	**10.81**	**1**	**10.81**	**11.37**	**0.001968**
Number of Wires and Electric Field	2.78	1	2.78	2.93	0.096782
Air Velocity and Electric Field	**140.63**	**1**	**140.63**	**147.86**	**0.000000**
1*2*3	**16.47**	**1**	**16.47**	**17.32**	**0.000222**
1*2*4	1.20	1	1.20	1.26	0.270278
1*3*4	**140.56**	**1**	**140.56**	**147.79**	**0.000000**
2*3*4	**174.57**	**1**	**174.57**	**183.55**	**0.000000**
Lack of Adjustment	**52.50**	**1**	**52.50**	**55.20**	**0.000000**
Pure Error	**30.44**	**32**	**0.95**		
Total Sum of Squares	39771.97	47			

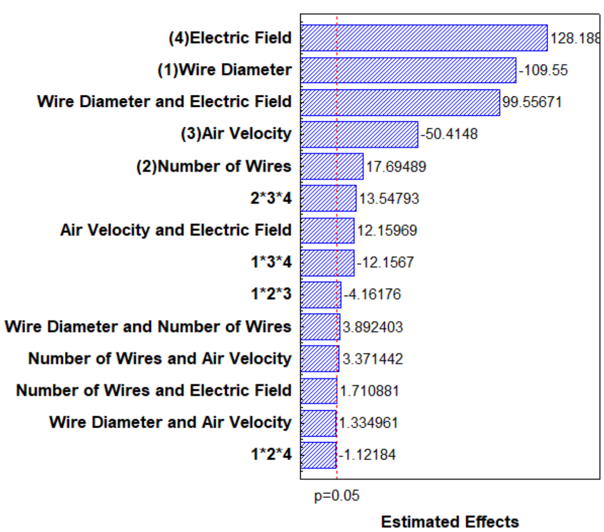

Figure 3: Pareto chart.

Finally, the response surfaces of the collection efficiency were plotted as a function of the factors evaluated. Fig. 4a presents a relation almost linear between the collection efficiency of the particles and the number of wires, and the results with 1 wire were lower than with 2 wires.

This linear relation was also observed with the collection efficiency and the wire diameter, however, in an inversely proportional way. Then, the larger the diameter, the lower the percentage of collected particles.

A similar behavior occurred between the collection efficiency with the air velocity and the wire diameter (Fig. 4b). The collection efficiency and the air velocity presented a linear relation, inversely proportional, achieving the highest efficiencies with smaller velocities.

Fig. 4c shows the relation between the collection efficiency with the wire diameter and the electric field. As observed previously, the relation between the efficiency and the wire diameter is linear and inversely proportional. On the other hand, the relation between the efficiency and the electric field is directly proportional, with a linear trend. Through the response surfaces, it is observed that the highest efficiencies were achieved when used smaller wires diameter and higher electric fields. Fig. 4d shows a relation between the collection efficiency with the electric field and the air velocity, discussed in the section. Therefore, the highest collection efficiencies were achieved with the wire diameter of 0.3 mm and the electric field of 3.38 kV/cm.

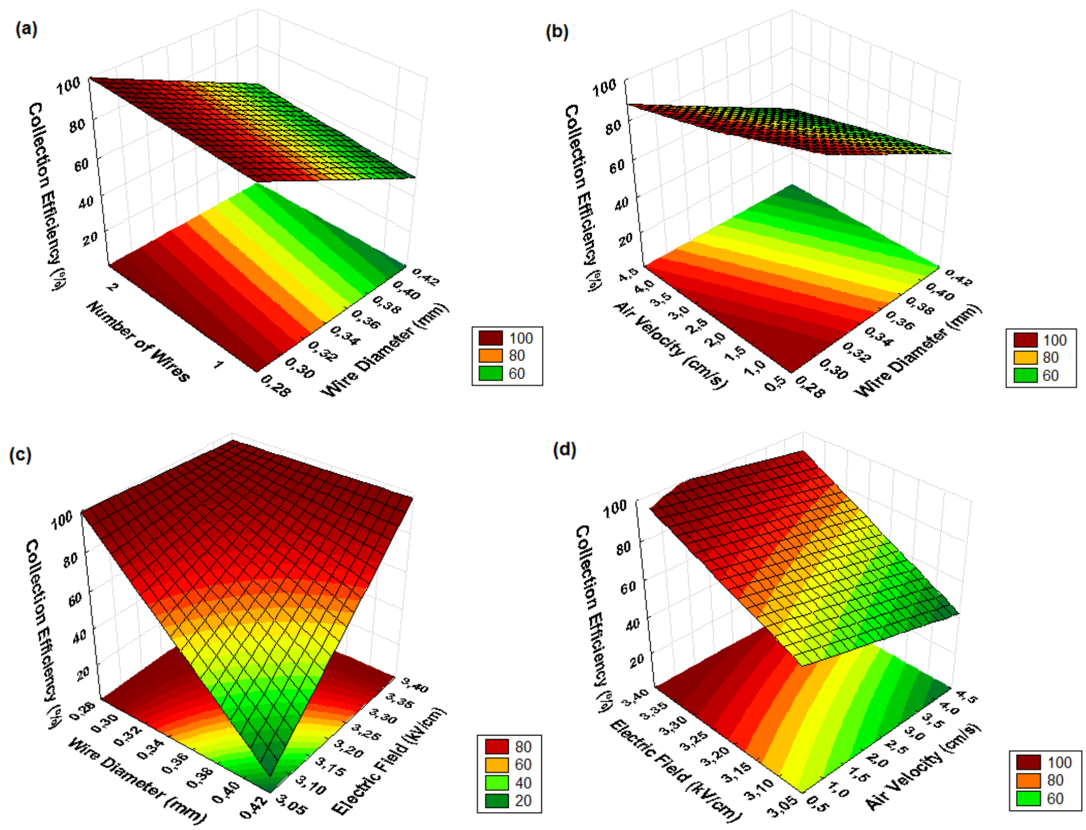

Figure 4: Response surface as a function of: (a) number of wires and wire diameter, (b) air velocity and wire diameter, (c) wire diameter and electric field and (d) electric field an air velocity.

4. CONCLUSIONS

The ANOVA analysis and the Pareto chart results showed that all factors were significant for the particle collection, especially the electric field and wire diameter. The wire diameter and the air velocity presented a negative effect, which means that the particle collection efficiency reduced (14-30%) with the increase of these parameters. On the other hand, the number of wires and electric field showed a positive effect, with an increase of over 36% on the particle collection. Through the analysis of the response surfaces, it was concluded that the highest collection efficiencies were achieved with the wire diameter of 0.3 mm and the electric field of 3.38 kV/cm. Therefore, it is possible to obtain collection efficiencies higher than 95% with a small number of wires and operating conditions that contribute to the electrostatic precipitation of particles.

ACKNOWLEDGMENTS

This study was financed by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES, Finance Code 001).

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