Factors that Influence the Tribocharging of Pulverulent Materials in Compressed-air Devices

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Abstract. Tribocharging of pulverulent materials in compressed-air devices is a typical multi-factorial process. This paper aims at demonstrating the interest of using the design of experiments methodology in association with virtual instrumentation for quantifying the effects of various process variables and of their interactions, as a prerequisite for the development of new tribocharging devices for industrial applications. The study is focused on the tribocharging of PVC powders in compressed-air devices similar to those employed in electrostatic painting. A classical 2^3 full-factorial design (3 factors at two levels) was employed for conducting the experiments. The response function was the charge/mass ratio of the material collected in a modified Faraday cage, at the exit of the tribocharging device. The charge/mass ratio was found to increase with the injection pressure and the vortex pressure in the tribocharging device, and to decrease with the increasing of the feed rate. In the present study an in-house design of experiments software was employed for statistical analysis of experimental data and validation of the experimental model.

1. Introduction
Tribocharging is a well-known phenomenon, with many applications ranging from powder coating to mineral processing and waste treatment [1-3]. Nevertheless, modeling of tribocharging processes involving granular or pulverulent materials is one of the less explored areas of applied electrostatics [4]. The charge attained by a particle in the tribocharging process depends on a relatively large number of factors. For understanding and quantifying their effects and their interactions, the few available theoretical models [3, 4] and empirical data [5, 6] are not of great help. Each case is characterised by a specific combination of potentially influent factors and experimentation is the only way for evaluating them. The classical experimental approach, which consists in obtaining the response $y$ for several values of each variable $x_i$, $i = 1, \ldots, n$, while fixing the values of the other $(n-1)$ variables, is expensive in terms of time and cost. For example in case of 4 variables and 5 experimental values to each of them, $5^4 = 625$ experiments are required.

Design of experiments (DOE) is a powerful tool to reduce the number of experiments to be carried out without sacrificing the quality of results [7, 8]. The advantage of this methodology is that it proposes a factorial experimentation, in which all factors are investigated simultaneously. Simple mathematical processing of DOE data enables a rather accurate evaluation of factor effects and interactions. DOE can also be used for determining the relationship $f$ between the factors affecting a process and the output of that process. The function $f$ can be then employed for predicting the optimal operating conditions of the process. Recently, DOE has been successfully employed for optimization and the robust design of an electrostatic separation process [9, 10, 11].
The main difficulty to surpass is the accurate characterization of process output: the charge/mass ratio of processed materials. One solution might be the use of virtual instrumentation (VI) [12]. The aim of the present paper is to demonstrate that DOE in association with VI can be an effective tool for modeling and optimization of a class of tribocharging processes.

The study is focused on the tribocharging of PVC powder in compressed-air devices similar to those employed in electrostatic painting [13]. Nevertheless, its conclusions could be of interest for a wide range of industrial applications, including the triboelectrostatic separation of powder mixtures in mining or food industry.

2. Design of experiments methodology

When the objective is screening of the various factors that might influence the outcome of a process, DOE recommends the use of two-level full factorial designs [7, 14]. In such experiments, each factor at each level is evaluated at an equal number of other factor-level combinations. In the case of 3 factors \( x_1, x_2, x_3 \) the experiment is conducted in accordance with a so-called \( 2^3 \) factorial design (points A…H in Fig. 1). The corresponding mathematical model is a first-order polynomial:

\[
y = f(x_i) = a_0 + \sum a_{i} x_i + \sum a_{ij} x_i x_j, \quad i = 1\pm3, j = 1\pm3, i \neq j
\]

The mathematical model contains \( p = 7 \) coefficients which, in the most simple case of 8 experiments in points A...H, are calculated as follows:

\[
a_0 = \frac{y(A) + y(B) + \ldots + y(H)}{8} \tag{2}
\]

\[
a_i = \frac{y(A) x_i(A) + y(B) x_i(B) + \ldots + y(H) x_i(H)}{8}, \quad \text{for } i = 1\pm3 \tag{3}
\]

\[
a_{ij} = \frac{y(A) x_i(A) x_j(A) + y(B) x_i(B) x_j(B) + \ldots + y(H) x_i(H) x_j(H)}{8}, \quad \text{for } i = 1\pm3, j = 1\pm3, i \neq j \tag{4}
\]

A straightforward way to validate this linear-interaction model is to calculate the value of the response \( y \) in the central point of the experimental domain (point M in Fig. 1), and compare it to the experimental value measured in the same point.

The statistical significance of the coefficients \( a_i \) and \( a_{ij} \) can be evaluated by calculating the residuals \( e_i \), i.e. the difference between the experimental value and the one predicted by the model, and estimating the variance

\[
s^2 = \frac{1}{n-p} \sum e_i^2 \tag{5}
\]

where: \( n \) is the number of experiments and \( p \) the number of coefficients of the model.

Figure 1. Representation of 11 experimental points.
A coefficient $a_i$ of the model is statistically significant if it satisfies Student’s test:

$$
 t_i = \frac{|a_i|}{s_i} > t_{crit}
$$

with $t_{crit}$ given in tables as function of the degrees of freedom $(n - p)$, and

$$
 s_i^2 = \frac{s^2}{n}
$$

The experimental set-up consists of a tribocharging device [13] provided with means to control the charge by adjusting the air pressure in different circuits (Fig. 2), an adjustable vibratory feeder to supply the powder to the tribocharging device, a modified Faraday cage connected to a digital electrometer (model 6514, Keithley Instruments), and a personal computer for data acquisition and processing. The injection pressure $p_{inj}$ determines the particle speed through the tribo-gun and the energy of particle-wall impacts; the vortex pressure $p_{vor}$ controls the turbulence of the motion. In standard powder coating applications of the tribo-gun, the dilution pressure $p_{dil}$ is used to modify the concentration of powder in the transported air. As in the present experiment, $p_{dil}$ is constant, powder concentration is controlled by adjusting the feed rate $M$ of the vibratory feeder.

![Figure 2. Schematic representation of powder tribocharging device](image)

The limits of the experimental domain were established based on the following constraints: $p_{inj} \leq 2.8$ bar, $p_{inj} > p_{dil} > p_{vor}$. Thus: $2$ bar $\leq p_{inj} \leq 2.8$ bar; $p_{dil}=1.7$ bar, $1$ bar $\leq p_{inj} \leq 1.2$ bar, the feed rate $0.2 \leq M \leq 0.8$ g/s. The ambient temperature was $19.5 \pm 0.5^\circ$C, while the relative humidity of ambient air $44.5 \pm 1.5\%$.

The charge measurement data were acquired during up to 30 seconds of steady-state operation of the tribo-gun. Measured data were processed by a virtual instrument (VI) developed in the LabView environment [15]. The VI commanded the grounding of the electrometer input every 2 s. In this way, it displayed the charge accumulated in the modified Faraday pail within 2 s intervals (Fig. 3). These data were then employed for the calculation of the charge/mass ratio.
3. Results and Discussion

The results of the 8 runs of the $2^3$ factorial design experiment are given in the first 8 lines of Table 1. The coefficients of the linear-interaction model were computed with (2), (3) and (4). The results of the three experiments carried out in the central point of the domain (lines 9 to 11 in Table 1) were employed for analysing the statistical significance of these coefficients, which express the effect of each factor (Table 2). Thus the charge/mass ratio $y$ can be expressed by the polynomial function:

$$y = 1.249 + 0.111 \cdot p_{inj} + 0.064 \cdot p_{out} - 0.174 \cdot M - 0.046 \cdot p_{inj} \cdot M - 0.0394 \cdot p_{out} \cdot M$$

(8)

### Table 1. Results of the $2^3$ full factorial experiment.

| Run No | Factors | Results |
|--------|---------|---------|
|        | $p_{inj}$ [bar] | $p_{out}$ [bar] | $M$ [g/s] | $Q$ [$\mu$C] | $m$ [g] | $Q/m$ [$\mu$C/g] |
| 1 (A)  | 2.0     | 1.0     | 0.2     | 12.74      | 10.98    | 1.16     |
| 2 (B)  | 2.8     | 1.0     | 0.2     | 16.00      | 10.90    | 1.46     |
| 3 (C)  | 2.0     | 1.4     | 0.2     | 14.20      | 10.49    | 1.35     |
| 4 (D)  | 2.8     | 1.4     | 0.2     | 16.90      | 10.05    | 1.68     |
| 5 (E)  | 2.0     | 1.0     | 0.8     | 11.88      | 12.18    | 0.92     |
| 6 (F)  | 2.8     | 1.0     | 0.8     | 14.13      | 12.74    | 1.11     |
| 7 (G)  | 2.0     | 1.4     | 0.8     | 12.60      | 12.23    | 1.03     |
| 8 (H)  | 2.8     | 1.4     | 0.8     | 15.20      | 13.01    | 1.15     |
| 9 (M)  | 2.4     | 1.2     | 0.6     | 17.07      | 13.51    | 1.26     |
| 10 (M) | 2.4     | 1.2     | 0.6     | 15.45      | 12.09    | 1.28     |
| 11 (M) | 2.4     | 1.2     | 0.6     | 15.63      | 12.11    | 1.29     |

Figure 3. Charge measurement graph displayed by the front panel of the virtual instrument for four different experimental conditions (the interval between two measurements is 2 s).
Table 2. Evaluation of the effects using Student’s $t$-test.

As expected, the charge/mass ratio $y$ increases with $p_{inj}$ and $p_{vor}$, while it decreases with the increase of the feed-rate $M$. The charge/mass ratio in the centre of the experimental domain predicted by the linear-interaction model is 1.249 $\mu$C/g. This value is close the average of the experimental values measured for the same point: 1.26 $\mu$C/g, which prompted the validation of the linear model (8).
4. Conclusions
Tribocharging of insulating powders in compressed-air devices is a multiple-factor process that can be effectively modeled and optimized by using the DOE methodology. With virtual instruments facilitating data acquisition and processing, DOE is likely to be employed on a wider scale for the optimization of various electrostatic processes that make use of tribocharging phenomena, such as the separation of mixed powders in mining or food industry.

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