Premises for Statistic Control of a Tribocharging Process for Granular Materials

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Abstract— This paper aims to identify the appropriate sampling duration for a tribocharging process in order to compute the capability indexes and set up a statistical control procedure. The outcome of the process is evaluated as the ration between the charge and the mass of the granules that exit the tribocharger during a given laps of time. A virtual instrument developed in LabWiew was used in conjunction with a Faraday cage connected to an electrometer and with an electronic scale, to simultaneously measure the charge and the mass of tribocharged granular plastics, for fixed sampling durations.

I. Introduction

Triboelectrostatic separation of plastic waste is a technology that has already proven its efficiency in the recycling of plastic wastes [1, 2]. The main challenge in designing such a technology for a new application is to control the tribocharging of granular plastics [3, 4], a process that is sensitive at the variation of a multitude of factors, such as particle size, thermal or chemical conditioning of the materials, ambient temperature and humidity [5].

Statistical Process Control (SPC) is a method widely employed in many industrial applications for detecting non-conformities by monitoring the process trough samples [6]. Non-conformities can be detected by statistical analysis of samples and adjustments can be made to the process in order to keep it within specifications. The sampling frequency must be chosen so that the assignable variations could be detected [7, 8].

In a triboelectrostatic separation process, the charge/mass (*Q/m*) ratio of a given species of granules that exit the tribocharger during a time interval Δt has to be within certain specification limits. Not enough deviated in the electric field, the poorly-charged granules (i.e., *Q/m* below the lower specification limit – *LSL*) are collected in the middling fraction (Fig. 1). The granules characterized by a *Q/m* beyond the upper specification limit (*USL*) are too much deviated by the electric field forces and, after impacting the electrode of opposite polarity, they are also collected with the middling.

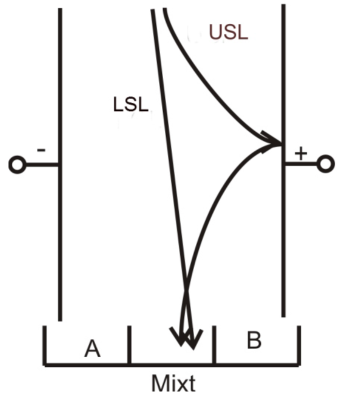


Fig. 1. Trajectories of granules charged beyond the upper specification limit (USL) and or below the lower specification limit (LSL), in a free-fall tribocharging separator.

These specification limits are established in relation with the material type (nature, shape, size, etc.) and separator operating parameters (high voltage level, electrodes length, distance between electrodes, etc.).

Taking into account these considerations, SPC is expected to be a useful tool for monitoring the tribocharging process of granular plastics [9]. The process variability may be characterized by using the capability indexes [10]. These indexes compare the interval of tolerance established for the Q/m ratio, with the dispersion of the values measured for a number of samples taken according to well-defined procedures. The critical issue is the duration Δt of the sampling. The shorter the duration Δt is, the less it disturbs the process. However, with measuring systems for mass m and charge Q having different time constants, choosing a too short sampling duration Δt may lead to erroneous conclusions. Due to the inertia of the mass measurement device, the values of m recorded at any given time t are slightly delayed with respect to the corresponding values of Q. The effect of this delay becomes negligible if the duration Δt of the sampling is longer.

As a first step towards the statistical control of plastic granules tribocharging process, the primary aim of this paper was to analyse the possibility of choosing the appropriate sampling duration Δt, based on the results of simple experiments that could be performed during the development phase of a new application. Thus, for the case of a vibratory tribocharger, a set of experiments were performed with virgin Polycarbonate (PC) granules in order to identify an appropriate sampling duration Δt for two distinct operating conditions (i.e., distinct values of the two variables of the process: material feed rate Φ and transport velocity v). A virtual instrument (VI) developed in LabView was used for simultaneous acquisition of mass m and charge Q of the granules in the tribocharging process [11, 12].

Then, another set tribocharging experiments were carried out with wastes PC granules, using the previously-determined sampling duration Δt, and the capability indexes were computed. The experiments pointed out the possibility of using control charts for monitoring the tribocharging process of this class of materials.

II. THEORETICAL ASPECTS OF CAPABILITY ANALYSIS

The capability expresses the ability of a certain process to respect the quality required by an application under well-defined operational conditions [13, 14]. The inherent variability of the factors may affect the quality of the process when it is beyond the specification limits. The difference between the upper specification limit (*USL*) and the lower specification limit (*LSL*) defines the interval of tolerance (*IT*) [14]. Usually, capability indexes are used to quantify how well a process respects the specifications.

The most common capability index C_p is defined as:

$$C_p = IT / 6\cdot\sigma = (USL - LSL)/6\cdot\sigma \tag{1}$$

where σ is the standard deviation of the process output variable *x* being monitored:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}{n-1}} \tag{2}$$

and $\bar{X}$ is the mean of *n* measured values X_i. The higher the value of the index, the more capable is the process: $C_p < 1$ (unsatisfactory), $1 < C_p < 1.33$ (low capability), $1.33 < C_p < 1.66$ (medium capability), $C_p > 1.66$ (high capability) [15].

Due to its simplicity, this index cannot provide an assessment of process centering (targeting). The more complex C_{pk} index takes into consideration both the variance of process (σ) and the position of the average value with respect to the upper and lower specification limits ($USL - \bar{X}$, $\bar{X} - LSL$) [16]:

$$C_{pk} = Min\left(\frac{USL - \bar{X}}{3\cdot\sigma}, \frac{\bar{X} - LSL}{3\cdot\sigma}\right) \tag{3}$$

The third capability index C_{pm}, introduced by Hsiang and Taguchi in 1985, is geared towards measuring the ability of a process to cluster around the target [17]. The C_{pm} index incorporates the variation of production items relative to the target value ($\bar{X} - \tau$) and the specification limits (*IT*).

$$C_{pm} = \frac{IT}{6\sqrt{\sigma^2 + (\bar{X} - \tau)^2}} \tag{4}$$

To accurately assess process capability, these three indexes should be jointly employed.

In order to take into account the uncertainty related to limited number of measurement employed for the computation of the standard deviation σ, the calculated capability indexes should be divided by so called "confidence coefficient" *k*. This coefficient represents (with a confidence of 95%) the ratio between the calculated (C_p, C_{pk}, C_{pm}) and actual (C_p^*, C_{pk}^*, C_{pm}^*) capability indexes [18]: $k = C_p/C_p^* = C_{pk}/C_{pk}^* = C_{pm}/C_{pm}^*$.

III. MATERIALS AND METHOD

The tribocharging experiments were performed on a vibratory feeder tribocharging device (designated as 2 in Fig. 2) with variable transport velocity *v* [cm/s]. The grounded metallic tray was covered by a Polyethylene Terephtalate (PET) sheet (3).

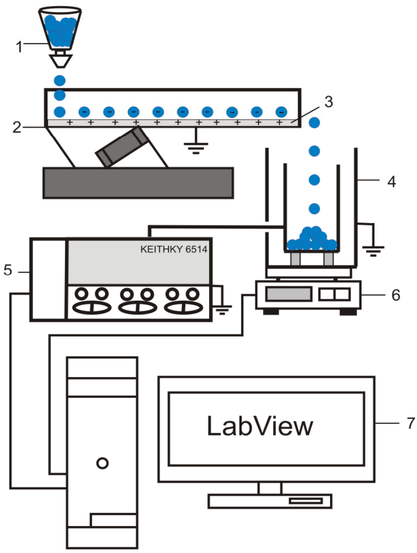


Fig. 2. Schematic representation of the experimental set-up for the study of tribocharging process of granular materials: 1 – vibratory device for feed rate control, 2- vibratory feeder tribocharging device, 3 – PET sheet on the vibratory feeder tray, 4 – Faraday pail, 5 – Keithley electrometer, 6 – electronic scale, 7 – computer.

The plastic granular material was disposed on the vibratory tray by a secondary vibratory feeder (1) with controllable feed rate Φ [g/s]. The granules got charged by repeated collision with the vibratory tray while moving in the longitudinal direction of the tray of the vibratory feeder[19-22].

The charged plastic granules were collected into a Faraday pail (4) connected to an electrometer (model 6514, Keitheley Instruments) (5). Their mass was also measured by an electronic scale (model 440-47N, Kern) (6). A virtual instrument developed in LabView environment [11] records independently the charge and the mass of the material collected during 0.5 s time intervals (Fig. 3). A computer (7) was used for the acquisition and processing of the data acquired during two to four minutes of steady-state operation of the tribocharging device.

As already mentioned in the Introduction of this study, the charge /mass ratio was considered as the response of the process:

$$Q_m = Q / m \quad \text{[nC/g]} \tag{5}$$

and was calculated for three sampling durations Δt = 0.5 s; 3 s; 6 s, corresponding respectively to one, six or twelve consecutive measurements.

Two tribocharging experiments were performed with virgin PC granules (Table 1) in order to identify the appropriate sampling duration Δt for two distinct operating conditions (i.e., distinct values of the two variables of the process: material feed rate Φ and transport velocity v) [19]. In the first tribocharging experiment, the operating parameters of the vibratory feeder were set as follows: Φ = 6 g/s and v = 7 cm/s. In the second tribocharging experiment, the feed rate was reduced at Φ = 5 g/s, and, in order to maintain a minimum cover rate on the vibratory tray, the transport velocity was adjusted at v = 6 cm/s.

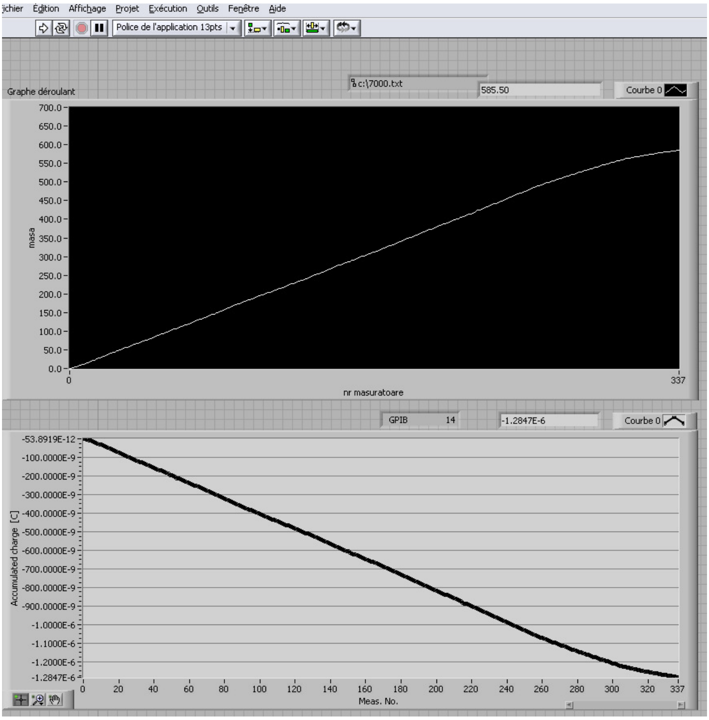
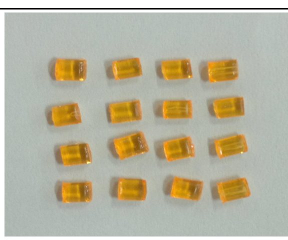
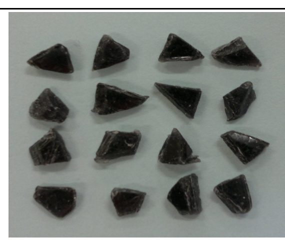


Fig. 3. Charge (a) and mass (b) evolution, recorded by the virtual instrument developed in LabView

TABLE 1: MATERIALS USED IN THE TRIBOCHARGING EXPERIMENTS

Virgin PC granules cylindrical shape, 3 x 3.6 mm	Waste PC granules irregular shape, ≈ 4.5 mm
	

The third tribocharging experiment was performed with waste PC granules (Table 1) in order to calculate the capability indexes of the tribocharging process based on the chosen sampling interval, Δt = 6 s. The operating parameters of the vibratory feeder tray were: Φ = 5 g/s and v = 6 cm/s.

During the experiments the temperature and the relative humidity of the ambient air have been almost constant (T = 23.2 ºC - 25 ºC, RH = 58% - 60 %).

IV. RESULTS AND DISCUSSION

Simultaneous charge Q [nC] and mass m [g] measurements acquired with the virtual instrument were processed as charge/mass ratio Q/m [nC/g] for different sampling durations (Table 2). For $\Delta t = 0.5$ s, and $\Delta t = 3$ s, the average value $\overline{X}$ and the standard deviation σ were calculated from the data of 50 samples (i.e., a total acquisition time of 50 x 0.5 = 25 s and 50 x 3 = 150 s = 2 min 30 s). In the case of $\Delta t = 6$ s, the computations were done for 30 consecutive samples (30 x 6 s = 180 s = 3 min).

Usually, studying the capability of a process implies the computation of the indexes C_p, C_{pk}, C_{pm} using the formulas (1) to (4), the interval of tolerance IT being imposed by the specifications of a given application, and the standard deviation σ being evaluated from the experimental data. In the present study, the capability issue is approached in a different way: the interval of tolerance IT corresponding to an imposed capability index (C_p or C_{pk} or C_{pm} = 1.33) is computed for the experimentally-determined value of the standard deviation σ.

In the first tribocharging experiment (Φ = 6 g/s, v = 7 cm/s), the average charge /mass ratio of PC granules was approximately Q/m = 0.8 nC/g for each of the three considered sampling durations, and the standard deviation σ varied between 0.086 nC/g (for the shortest sampling duration $\Delta t = 0.5$ s) at 0.029 nC/g (for $\Delta t = 6$ s).

TABLE 2: RESULTS OF THE FIRST AND THE SECOND TRIBOCHARGING EXPERIMENTS

	Φ = 6 g/s, v = 7 cm/s			**Φ = 5g/s, v = 6 cm/s.**		
	Δt = 0.5 s	**Δt = 3 s**	**Δt = 6 s**	**Δt = 0.5 s**	**Δt = 3 s**	**Δt = 6 s**
	Q/m [nC/g]					
$\overline{X}$	**0.8851**	**0.8032**	**0.793**	**1.05**	**1.03**	**1.03**
σ	**0.0861**	**0.04724**	**0.02918**	**0.1230**	**0.0607**	**0.0478**

For a sampling duration of $\Delta t = 0.5$ s, in order to obtain a real capability index $C_p^* = 1.33$, the computed capability index should be $C_p = 1.60$ [19]. Using the relation (1), the corresponding minimum interval of tolerance is:

$$IT = C_p \cdot 6\sigma = 1.60 \cdot 6 \cdot 0.086 = 0.82 \text{ nC/g} \quad (6)$$

This interval of tolerance, representing 100% from the average charge /mass ratio, would be too high for any triboelectrostatic separation process. For such an IT, the granules characterized by a charge/mass ratio Q_m near the upper specification limit would by strongly attracted towards the electrode of opposite polarity, collide with it and rebound into the middling fraction ("USL" trajectory in Fig. 1). On the other hand, the granules with a Q_m near the lower specification limit would also be collected in the middling fraction, as their trajectory (designated as "LSL" in Fig. 1) would only slightly be affected by the electric field forces.

This minimum interval of tolerance is largely over-estimated, as the sampling duration Δt is too short, as compared to the time constant of the mass measuring system. The values of m recorded at any given time t being slightly delayed with respect to the corresponding values of Q, the experimental dispersion evaluated under these circumstances is larger than the actual one.

For Δt = 3 s, the values of charge/mass ratio Q_m are more uniform and the standard deviation is reduced at σ = 0.0472 nC/g. In this case, the minimum interval of tolerance corresponding to an actual capability index of C_p = 1.33 (C_p^* = 1.6) is:

$$IT = 1.60 \cdot 6 \cdot 0.0472 = 0.453 \text{ nC/g} \quad (7)$$

This interval of tolerance that represents about 50% of the average Q_m can be easier accepted for the tribocharging process of granular material in view of tribo-electrostatic separation.

In the case of a sampling duration Δt = 6 s, due to the fact that are only 30 measurements, a real capability index C_p = 1.33 corresponds to C_p^* = 1.70. The standard deviation calculated from the results in Table 2 being σ = 0.02918 nC/g, the interval of tolerance is:

$$IT = 1.70 \cdot 6 \cdot 0.02918 = 0.2976 \text{ nC/g}, \quad (8)$$

which represents only 37.5% of the average charge/mass ratio. This result put in evidence that for a longer sampling duration, the measurement results are more homogenous and the interval of tolerance can be diminished.

In the second tribocharging experiment the material feed rate and transport velocity were simultaneously diminished (Φ = 5 g/s, v = 6 cm/s), so that the collecting feed rate of granules in the Faraday cage was also reduced. The values of standard deviation σ indicate a higher non-homogeneity of granules charge (Table 2). The intervals of tolerance corresponding to an actual capability index C_p = 1.33, for the three sampling intervals, Δt = 0.5, 3 and 6 s, are:

$$IT_{0.5\ \text{s}} = 1.6 \cdot 6 \cdot 0.123 = 1.18 \text{ nC/g} \quad (9)$$

$$IT_{3\ \text{s}} = 1.6 \cdot 6 \cdot 0.0607 = 0.5827 \text{ nC/g} \quad (10)$$

$$IT_{6\ \text{s}} = 1.7 \cdot 6 \cdot 0.0478 = 0.4875 \text{ nC/g} \quad (11)$$

In this case, an acceptable interval of tolerance IT of about 50% of the average charge/mass ratio Q_m is obtained only for the sampling duration Δt = 6 s (corresponding to a standard deviation σ = 0.0478 nC/g).

The results of the third tribocharging experiments performed with waste PC granules on the vibratory feeder tray at a feed rate of Φ = 5 g/s and a transport velocity v = 6 cm/s, for a sampling interval Δt = 6 seconds are presented in Table 3. The average charge/ mass ratio and the standard deviation computed with the data from Table 3 are: $\overline{X}$ = 1.14 nC/g; σ = 0.0321 nC/g.

TABLE 3: RESULTS OF THE THIRD TRIBOCHARGING EXPERIMENTS

Sample No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Q/m [nC/g]	1.08	1.14	1.11	1.17	1.12	1.18	1.12	1.13	1.19	1.13
Sample No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Q/m [nC/g]	1.18	1.13	1.17	1.13	1.08	1.13	1.11	1.12	1.13	1.19

The target value was set near the average charge/mass ratio, at τ = 1.15 nC/g. The interval of tolerance was computed as a percentage α of this target. With α = 37.5% (i.e., the lowest value for the minimum interval of tolerance calculated from the previous sets of tribocharging experiments):

$$IT = 37.5\% \cdot 1.15 \cong 0.43 \text{ nC/g} \quad (12)$$

Consequently, the specification limits were set at:

$$USL = \tau + IT/2 \cong 1.15 + 0.21 = 1.36 \text{ nC/g} \quad (13)$$

$$LSL = \tau - IT/2 \cong 1.15 - 0.21 = 0.94 \text{ nC/g} \quad (14)$$

The process capability index is:

$$C_p = IT/6\cdot\sigma = 0.43/ 6\cdot 0.0321 = 2.23 \quad (15)$$

The performance index of the process C_{pk} was also calculated with (3):

$$C_{pk} = (1.14 - 0.94)/3\cdot\sigma = 0.2/ 3\cdot 0.0321 = 2.15 \quad (16)$$

and the Taguchi capability index with (4):

$$C_{pm} = 0.43/\{6\cdot[0.0321^2 + (1.14 - 1.15)^2]^{1/2}\} = 2.17 \quad (17)$$

In order to take into account the uncertainty related to the limited number n of measurements employed for the computation of the standard deviation, these values were divided by the confidence coefficient k. For $n = 20$ measurements, $k = 1.24$ [18] and the recalculated (i.e., actual) values for capability indexes are:

$$C_p^* = 1.8,\ C_{pk}^* = 1.73,\ C_{pm}^* = 1.75 \quad (18)$$

For an interval of tolerance of 37.5 % from the average charge /mass ratio, all capability indexes are higher than 1.33, indicating that, in the conditions presented above, the tribocharging process on the vibratory feeder is capable to meet the specifications.

V. Conclusions

The homogeneity of charge acquired by the plastic granular materials in the tribocharging process has a significant influence on the outcome of triboelectrostatic separation process. A good separation imposes a narrow interval of tolerance for the charge/mass ratio of tribocharged materials.

The sampling duration affects the results of the experiments aimed at evaluating the capability of the tribocharging process. With measuring systems for mass and charge having different time constants, choosing a too short sampling duration lead to an overestimation of process variability. The effect of delay between the mass and charge values recorded at any given time becomes negligible if the duration of the sampling is longer. However, calculating the charge/mass rate over too long a sampling duration is not recommended either, as some information on the undesirable fluctuations of the outcome of the process might be lost.

The appropriate sampling duration depends on the operating condition of the tribocharging device. In the case of the vibratory tribocharger, the sampling duration must be correlated with the material feed rate and transport velocity.

The vibratory tribocharger under test was found capable to meet the specifications imposed by the electrostatic separation of granular plastics.

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