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Experimental study of a vibratory-type triboelectric charging device

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ABSTRACT

A high electrical charge to mass ratio of the particulates is a crucial for the successful electrostatic separation of granular plastic waste mixtures. The aim of the present study was to optimize the operation of a vibratory-type triboelectric charging device for two types of the plastic granules: Acrylonitrile Butadiene Styrene (ABS) and High Impact Polystyrene (HIPS). The triboelectric charger is composed of an electromechanically-vibrated metal plate covered with a thin sheet of Polyethylene Terephthalate (PET). The feed rate, the displacement velocity of the particles, and the length of the vibrating plate were the controllable variables of the process. A series of tribo-charging experiments were conducted on ABS and HIPS granules originating from industrial waste, with a particle size of 1 to 2 mm. The performance of the vibratory-type-triboelectric charging device was evaluated by measuring the electrical charge acquired by the granules. The response surface methodology was employed for the optimization of the process.

Keywords: electrostatic separation, triboelectricity, charge per mass ratio, vibrating plate, charging particles.

1. Introduction

Periodic renewal of electrical and electronic equipment is a major way to improve their performances. The consequence of this renewal is the accumulation of massive stocks of end-of-life materials, which are converted into waste streams, which cause serious environmental issues [1]. The recycling of Waste Electrical and Electronic Equipment (WEEE) is currently part of the eco-conception approach aimed at optimizing the end-of-life management of these products. The WEEE contain many valuable materials [2,3], including plastics, which have seen explosive growth in recent decades due to their low cost, durability, and lighter weight than competing materials. Triboelectrostatic separation is an effective method that is widely used in the recycling industry to recover valuable plastics [4-6]. The difference in surface properties of the various plastics enables their electric tribocharging in view of the selective sorting in a high-intensity electric field [3,6], such as the one generated between the electrodes of a free-fall electrostatic

separator. The dry electrostatic processing of plastic particles [5-7], has several notable advantages such as high efficiency, low cost, and the capability of processing a relatively wide range of materials [5-8].

A tribocharger is device used to charge different materials through contact or friction [1,8,9]. Triboelectric charging is due to two types of collisions: between two particles or between a particle and the walls of the device [2,6,10,11]. The charged mixture is then separated under the action of the intense horizontal electric field created by the two vertical electrodes of a free-fall separator [12]. The problem is that part of the initially charged product is not found in the compartment reserved for it. This is due to the fact that not all the particles are sufficiently charged, and the force of gravity exerted on them surpasses the electrostatic force. As a matter of fact, the movement of plastic particles introduced into an intense electric field does not depend on the amount of charge but on the charge per mass ratio [14].

Many studies have been conducted on various laboratory-scale triboelectric charging devices [4, 5, 15-20]. Vibratory trays [4], cyclones [16], fluidized beds [17], rotating cylinders [18], propeller-type devices [19] [20], were investigated with the aim to determine their optimum operating parameters. All these papers are focused on demonstrating that these devices can be successfully used as tribochargers of insulating plastic granules. In most cases the optimum values of the operating parameters of these tribochargers are established by experimental modelling the tribocharging process using the response surface method. Nevertheless, this kind of studies are not sufficient for attaining a comprehensive understanding of the complex multi-variable physical phenomenon of triboelectric charging of granular materials.

The objective of this work is to validate an experimental procedure for the optimization of vibratory-type triboelectric charging processes. The novelty of the approach adopted by the authors is that it also considers the charge accumulation at the surface of the vibratory plate of the tribocharge. The charge build-up depends on the nature of the particles that are conveyed and of the insulator layer that covers the vibratory plate; it might affect the outcome of the tribocharging of granular mixtures. The design of experiments methodology was used to identify the operating conditions of the device for obtaining the highest possible electrical charge per mass ratio in the case of ABS and HIPS granules recovered from industrial waste and characterized by a particle size ranging from 1 to 2 mm.

2. Experimental device

The experimental triboelectric device used is presented in Fig.1. The standard plate of a vibratory feeder (Vibra France, model APB4=30) has been replaced by a stainless-steel plate with length $l_0 = 230$ mm, width $l = 100$ mm and height $h = 30$ mm, covered with a thin layer of PET (0.2 mm). To prevent charge accumulation at its surface, the vibrated metallic plate is connected to the ground. A potentiometer, graduated from 0 to 10 graduations, is used to adjust the amplitude of vibrations in relation to the velocity v [cm/s] granule movement at the surface of the plate. A second vibrating feeder (Fischer Bioblock, model DR 100) is used to

control the feed rate ϕ [g/s] of the plastic pellets on the PET covered vibrated plate. The charge acquired by the plastic pellets is measured by collecting them at the outlet of the plate in a Faraday pail, connected to an electrometer (Keithley, model 3514).

3. Materials and method

In this study, a series of experiments were carried out on samples of 100 g of either ABS or HIPS granules (Fig.2), with an average pellet size of 1 to 2 mm, originating from out-of-use computer casings, after shredding and grinding. The plastic granules were provided by a WEEE recycler (APR2, Bonnières sur Seine, France). The PET was chosen as material for the thin insulating layer at the surface of the vibrated plate based on its median position in the triboelectric series. In this way, the ABS and HIPS granules will acquire respectively positive and negative charges by collision with it.

A first series experiments were carried out to study the behavior of the PET material covering the vibrating plate at the passage of the ABS and HIPS granules. Thus, 52 samples of 100 g ABS particles, prepared from the 5.2 kg of product available at the laboratory, were successively passed on the PET-covered vibrating. After each passage of such a sample, the electric charge accumulated on the PET sheet was measured with the device shown in Fig. 3. When the measuring device is placed over the charged PET sheet (2), a charge of opposite polarity is induced on the lower surface of the measuring electrode (3). To maintain the neutrality of this electrode, its upper surface will have the charge of the PET sheet and will be measured by the electrometer. The electric charge density was then calculated as the ratio between the charge indicated by the electrometer and the area of the measuring electrode. In a similar way, the electric charge density at the surface of the PET-sheet was measured after the successive passages of 52 samples of 100 g HIPS particles.

The second and third series of experiments were carried out to determine the charging tendency of ABS and HIPS granules after separate and repeated passages on the PET sheet. The study was aimed at evaluating the influence of the three controllable variables of the process: pellets displacement velocity v [cm/s] on the vibrating plate, the pellets feed rate ϕ [g/s], and the vibrating plate length L [cm]. Three sets of preliminary experiments were performed to determine the range of variation of the three controllable variables on the vibro-triboelectric process: $u_1 = v$, $u_2 = \phi$, $u_3 = L$.

The study of feed rate ϕ effect was conducted with 100 g samples of ABS and 100 g samples of HIPS, at three constant values of the displacement velocity v : 5,67 cm/s, 7 cm/s, and 9,1 cm/s, under stable atmospheric condition (humidity $RH=53\% \pm 2\%$, temperature $T=19.3^\circ \pm 1^\circ\text{C}$), the length of the tray being $L = 23$ cm. The study of displacement velocity v effect was performed on the $L = 23$ cm vibrating tray, with the same quantities of materials, under similar ambient conditions, at three constant values of the feed rate ϕ : 2,86 g/s, 3, 86 g/s and 5 g/s,

New samples were used in each experiment concerning the effects of granule feed rate and granule velocity. For the study of the effect of vibrated plate length L , the same sample was passed one to five times in the tribocharger, corresponding to $L = 23$ cm; 46 cm; 69 cm; 92 cm; 115 cm (feed rate: 3.8 g/s; displacement velocity: 7.7 g/s).

To model the process and determine the optimal operating parameters of the tribocharger the design of experiments methodology was used [20]. A composite factorial experimental design [22] was conducted to obtain the response "y" of the process, given by the following general formula:

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_{11}x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 + a_{12}x_1x_2 + a_{13}x_1x_3 + a_{23}x_2x_3 \quad (1)$$

With a_i and a_{ij} are the coefficients of the quadratic model and x_i , $i = 1, 2, 3$ are the normalized centered values of each factor u_i .

$$x_i = (u_i - u_{ic})/\Delta u_i = u_i^* \quad (2)$$

$$u_{ic} = (u_{imax} + u_{imin})/2 ; \Delta u_i = (u_{imax} - u_{imin})/2 \quad (3)$$

For the factors considered in this study (v , ϕ and L), the quadratic response model of the specific charging acquired by the ABS and HIPS pellets takes the following form:

$$y = a_0 + a_1v^* + a_2\phi^* + a_3l^* + a_{11}v^{*2} + a_{22}\phi^{*2} + a_{33}l^{*2} + a_{12}v^*\phi^* + a_{13}v^*l^* + a_{23}\phi^*l^* \quad (4)$$

The analysis of the obtained experimental results was performed with the software MODDE 5.0 (Umetrics 1999) [23]. It calculates the a_{ij} coefficients of the mathematical model and determines the best factor settings to optimize the procedure. The program evaluates two statistical criteria: the "goodness of the adjustment" (R^2) and the "quality of the prediction" (Q^2). The numerical values of R^2 and Q^2 must be close to the unity for a good model.

4. Results and Discussion

4.1 Charging of the PET sheet

The outcome of the experiments regarding the evolution of the charge density at the surface of the PET sheet exposed to 52 successive passages of 100 g samples of ABS and HIPS are shown in Fig.4. The collisions between plastic granules and PET sheet ensure the charge transfer between the PET sheet and both ABS and HIPS particles. The charge density on the PET vibrating plate approaches saturation, attaining 20 nC/cm² after 45 passes of the ABS granules. In contrast, the density of charge increases gradually with the number of passes of the HIPS granules, but 52 were not enough to saturate the PET sheet. As expected, the charge transfer depends on the nature of the materials in contact. A larger amount of charge was transferred at each ABS-PET contact than in the case of HIPS-PET contact and this caused a faster saturation of the insulating sheet at the surface of the vibrated plate.

This observation is confirmed by the results of the experiments involving separate and repetitive passages of 100 g of either ABS or HIPS granules on the PET sheet (Fig. 5). The ABS granules tended to converge towards saturation after 5 consecutive passes, while HIPS granules saturated on the PET coated vibrated plate only after 7 consecutive passes. These results point out the fact that increasing the length of the PET-covered plate beyond a certain value will not lead to better charging, as the granules attain their saturation charge. From a practical point of view, increasing the charger length is counter-productive, as it will increase the size of the tribocharger (and its energy consumption).

4.2 Determination of the variation range of the controllable parameters

4.2.1 Feed rate

For each measurement point, the experiments were triplicated (the standard deviation was less than 5%), and the results are summarized in Fig. 6. From Fig.6 .a, it can be seen that the best charge per mass ratio for ABS is obtained for a velocity of 7 cm/s and for feed rate values between 2 g/s and 5 g/s. On the other hand, the best charge per mass ratio for HIPS is obtained for a velocity of 7 cm/s and for feed rate values between 2 g/s and 2.85 g/s, as illustrated in Fig. 6.b. Hence, the variation feed rate for the composite factorial design to model and optimize the tribo-charging process was limited to the range $\phi = 2$ g/s to $\phi = 5$ g/s (Table 1).

In a prior study [6], it had been observed that when ϕ is too high and the velocity v [cm/s] is too low this induces an accumulation of the granules on the vibrating plate. In these circumstances, some of the granules did not triboelectrically charge, as they should, because they did not contact the PET sheet. Contrarily, the triboelectric process becomes ineffective at a high vibration velocity v and a very low feed rate ϕ as the number of interactions between the granules and the PET sheet is decreased, as it is stated also in [6]. To obtain an even distribution of the plastic granules on the vibrating plate and to guarantee that the ABS and HIPS granules collide with the PET sheet frequently enough, it is imperative to correlate these two factors.

4.2.2 Granules velocity on the surface of the vibrated plate

According to the results shown in Fig. 7.a, the best charge per mass ratio for ABS was obtained at a feed rate of 3.86 g/s for a velocity ranging from 6.84 cm/s to 9.71 cm/s. The best charge per mass ratio for HIPS was obtained at a feed rate of 5 g/s for velocities ranging from 5.67 cm/s to 6.84 cm/s, as shown in Fig. 7.b. Thus, the range of v for the composite factorial design used to simulate and improve the tribo-charging process was chosen to be from $v = 6$ cm/s to $v = 9.4$ cm/s (Table 1).

These results confirm that the mechanical characteristics of the collisions have a significant influence on the electrical charge exchange between the granules and the solid surface [14]. The amount of electrical charge that is transmitted between the ABS granular and HIPS granular respectively and the PET-coated surface of the vibrating device depends on the type of contact, the duration of the contact, and the interaction energy. All these factors are related to the velocity v at which the granules move across this surface [4].

4.2.3 Vibrated plate length

The electrical charge acquired by the plastic granules is likely to be influenced by the length L [cm] of the vibrating plate [4,6]. Indeed, the longer the plate, the more collisions occur between the ABS and HIPS granules respectively and the PET sheet. Experiments were carried out by passing the ABS and HIPS granules respectively through the tribocharger n times ($n = 2...7$), so that the total length can be expressed as $L = n l_0$. The results shown in Fig.5 (which represent the average of three passes) show that beyond $n = 5$, which corresponds to a plate length $L = 115$ cm, the charge to mass ratio tends to saturate for ABS granules. In order to avoid this saturation zone, the upper limit of the length L was set at 92 cm which corresponds to $n = 4$, while the lower limit was set at $L = 46$ cm which corresponds to $n=2$ as shown in Table 1.

5. Experimental modeling of the tribo-charging process

The results of the experiments performed according to the design of experiments methodology on samples of 100 g of ABS pellets and 100 g of HIPS pellets of sizes 1 to 2 mm are presented in Table 2. Each measured point corresponds to the average of three trials, performed under stable atmospheric conditions of humidity $RH= 61\%, \pm 2\%$ and temperature $T= 21^\circ \pm 1C$. The mathematical models obtained using MODDE 5.0 software are given in Table 3. The obtained charge per mass ratio models depend on v , ϕ and L parameters.

5.1 Effect of velocity

In Fig. 8.a and Fig. 8.b, the specific charge per mass ratio of ABS and HIPS granules is presented as a function of granule displacement velocity. The model shows an approximately linear rise in the charge per mass ratio from $v = 6$ cm/s to $v = 7.7$ cm/s. With a displacement speed of 7.5 cm/s, the maximum value of the ABS charge per mass ratio is 1.20 nC/g. However, for HIPS, this maximum is -1.29 nC/g for a displacement speed of 7.7 cm/s. Hence, the variation of the charge to mass ratio is slightly different for the two materials. This trend of increasing charge per mass ratio is justified by the movement of granules with shorter jumps and a higher number of collisions with the vibrating plate. For ABS and HIPS, the charge per mass ratio declined at speed values beyond 7.5 cm/s and 7.7 cm/s, respectively. Higher velocities imply higher jumps and more energetic collisions between the granules, but fewer hits mean that the granules are accumulating less charge.

5.2 Effect of feed rate

The charge per mass ratio of the ABS pellets, shown in Fig. 9.a, rose with increasing pellets feeding rate on the vibrating plate from 2.6 g/s to 3.8 g/s before falling sharply. On the other hand, the charge per mass ratio of the HIPS granules decreased linearly with an increase in the rate at which the granules were fed to the vibrating plate as illustrated Fig. 9.b. The mathematical model indicates that the highest absolute value of the charge per mass ratio was for ABS 1.20 nC/g at a feed rate of 3.6 g/s and for HIPS -1.6 nC/g at a feed rate of 2.6 g/s. These outcomes are attained for length $L=69$ cm and $v = 7.7$ cm/s. The fact that the granules have less impacts on the vibrating plate can explain why specific charge decreases at increasing granule deposition velocities.

5.3 Effect of length L

As expected, the charge per mass ratio increased with the vibrating plate length L . The same result was observed for both ABS and HIPS, as shown in Fig10.a and Fig10.b. This leads to predicting that a vibrating plate length of 92 cm would yield the best results, with charge per mass ratios of 1.30 nC/g for ABS pellets and -1.65 nC/g for HIPS pellets.

5.4 Velocity and feed rate interaction

Contour plots provided by MODDE.5.0 and depicted in Fig.11 highlight the effects of the two control variables: the velocity v of particle movement on the vibrating plate and the rate ϕ of granule deposition on the vibrating plate. In the case of ABS granules, shown in Fig.11.a, the model predicts the highest charge per mass ratio of 1.177 nC/g for velocities range values between 6.70 cm/s and 8.30 cm/s, with a feed rate varying between 2.6 g/s and 4.5 g/s. For the HIPS material, shown in Fig.11.b, the model predicts

the highest charge per mass ratio value of -1.58 nC/g, for velocities ranging between 6.5 cm/s and 9.1 cm/s, with a feed rate varying between 2.6 g/s and 3 g/s. This result can be explained by the synergetic action of the two control variables in the mentioned intervals, to generate collisions of the granules and the vibrating plate efficiently enough to obtain energetic and repetitive impacts that induce a rather high charge per mass ratio.

6. Conclusions

The present paper validates an experimental procedure for the optimization of a vibratory-type triboelectric charging processes. The novelty of the approach adopted by the authors is that it also considers the charge accumulation at the surface of the vibratory tray.

1) The charge build-up depends on the nature of the particles that are conveyed and of the insulator layer that covers the vibratory plate; it might affect the outcome of the tribocharging of granular mixtures.

2) The obtained results show that the behavior of the PET during the passage of the ABS and HIPS granules separately influences the charges transfer. Thus, the charge to mass ratio is strongly influenced by the intrinsic properties of the vibrating plate

3) The charge per mass ratio increases with the length of the vibrating plate to the limit of saturation of the plastic particles, after which the exchange of charge between the two materials ceases.

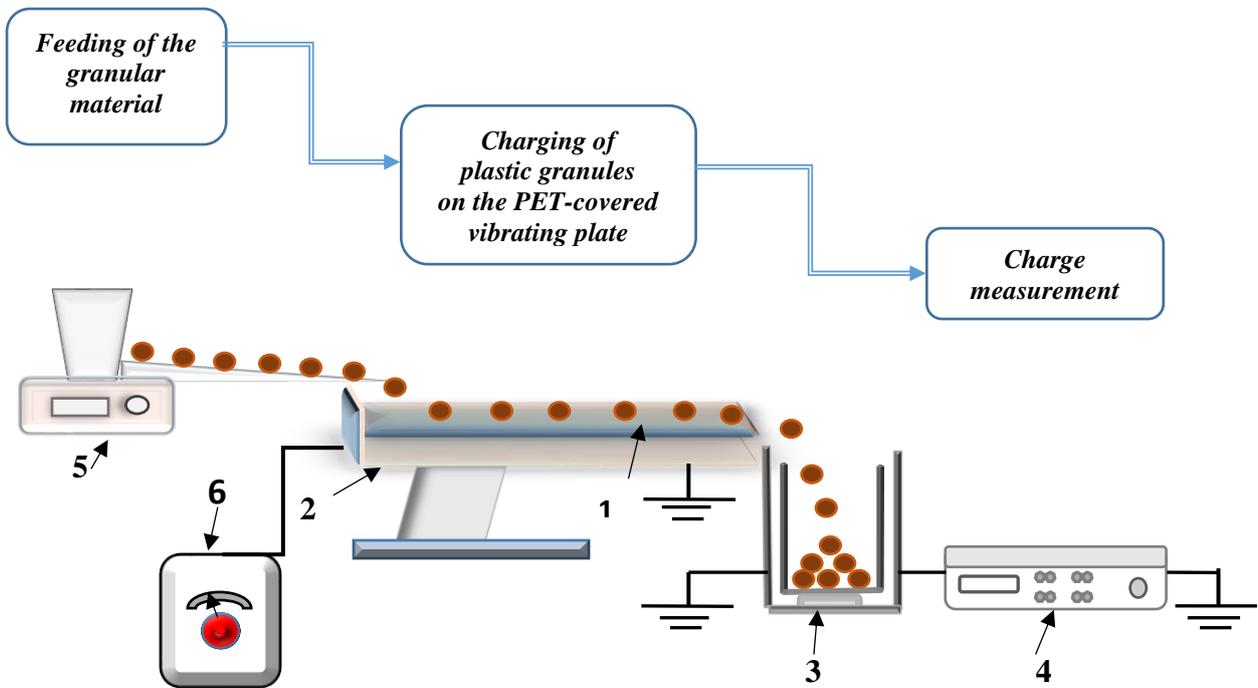
4) The material feed rate and the transport velocity of the particles on the vibrating feeder should be correlated, to obtain good performances.

5) The multivariable vibro-triboelectric charging process can be effectively modeled and optimized utilizing experimental design techniques.

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(a)



(b)

Fig. 1. Experimental setup for the study of the tribo-charging process of granular materials: (a) Schematic representation, (b) Photograph of the laboratory equipment: (1) Vibratory device; (2) PET sheet cover of the vibrating plate; (3) Faraday pail; (4) Electrometer (Keithley, model 3514); (5) Vibratory device for feed rate control; (6) Vibration amplitude controller graduated from 0 to 10.

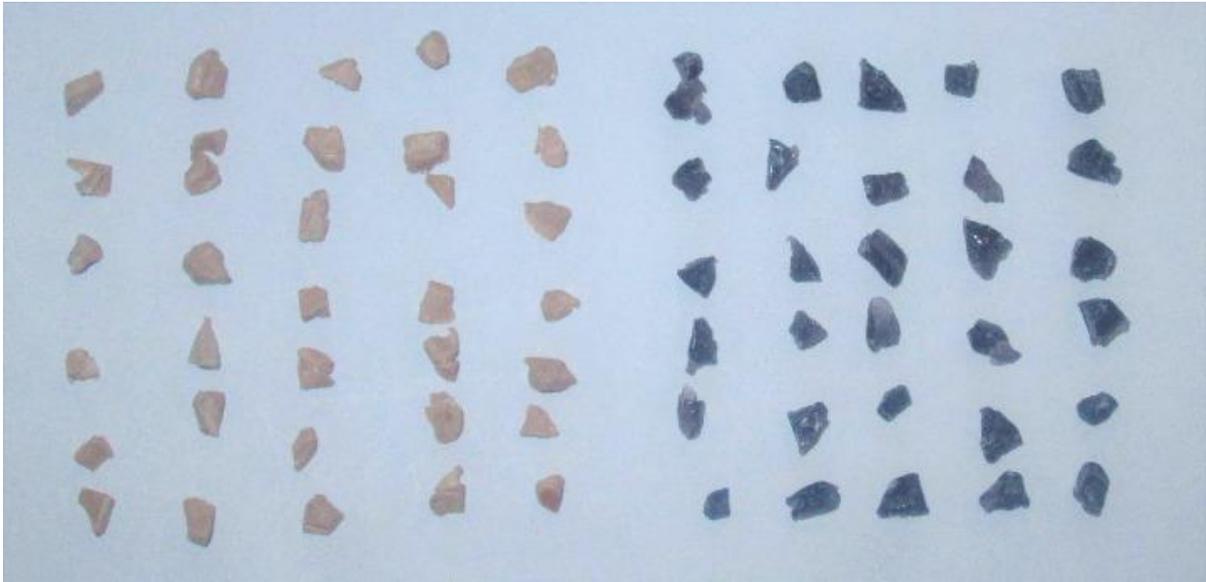


Fig. 2. Photograph of the materials used in the experiments: ABS on the left side, HIPS on the right side

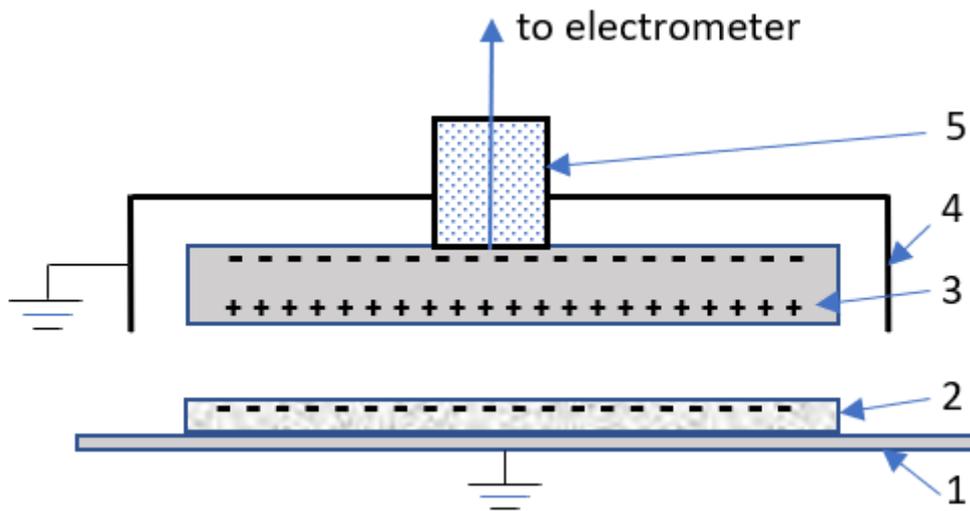


Fig. 3. Schematic representation of the surface charge measuring device: (1) tray of the vibratory feeder; (2) PET sheet; (3) measuring electrode (copper plate, 90 mm x 55 mm); (4) electrostatic shield; (5) insulating support.

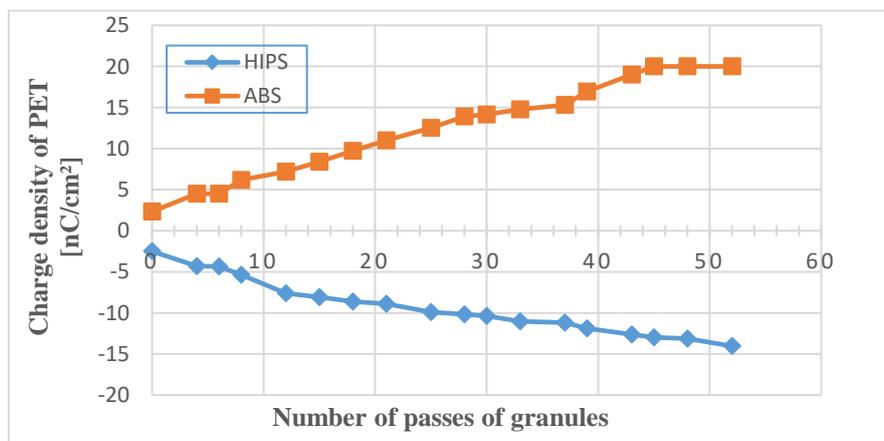


Fig 4. Graph showing the charge density of the PET material as a function of number of passes of the ABS and HIPS granules. (feed rate: 3.8 g/s; displacement velocity: 7.7 g/s)

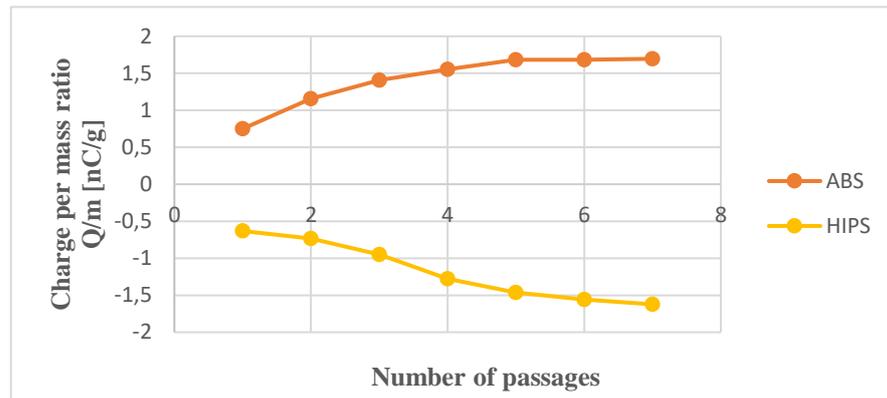


Fig 5. Charge per mass ratio of ABS and HIPS granules plotted as a function of the number of passes in the tribocharger.

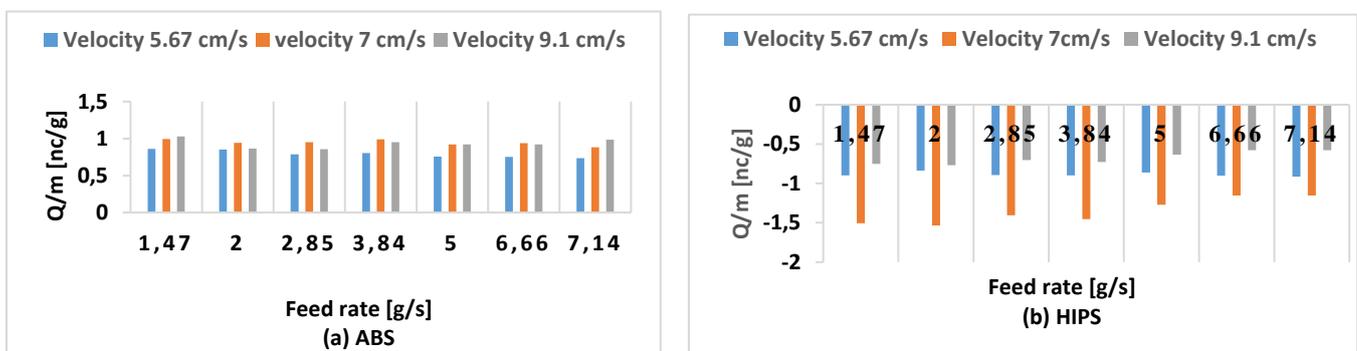


Fig. 6 Charge per mass ratio of ABS (a) and HIPS (b) granules, as function of the feed rate, at constant values of displacement velocity at the surface of the vibrating plate of the tribocharger. (tray length: 23 cm)

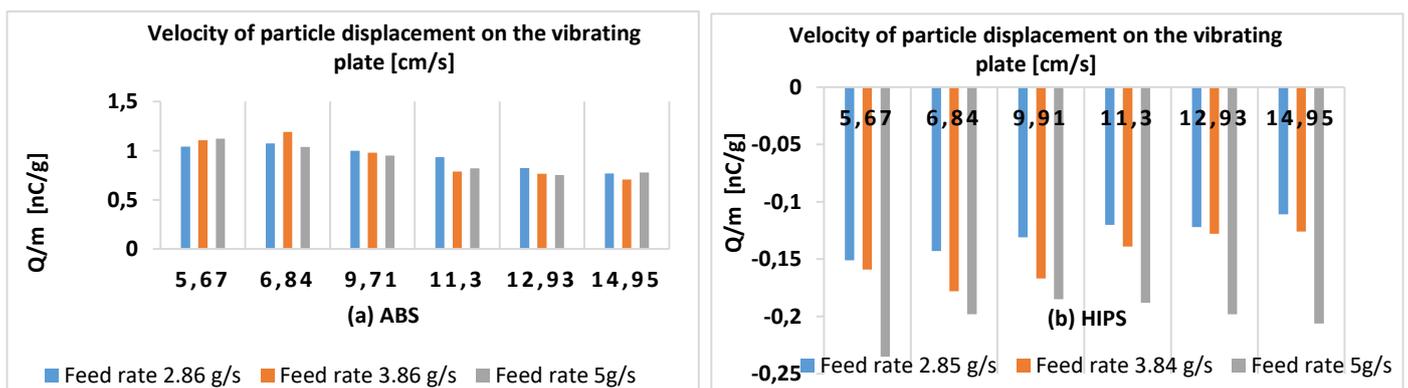


Fig. 7. Charge per mass ratio of ABS (a) and HIPS (b) granules, as a function of the displacement velocity at the surface of the vibrating plate of the tribocharger, at constant values of the feed rate. (tray length: 23 cm)

Table 1. The domain of variation of the three factors considered in the present study.

Value	MIN	CENTRAL	MAX
Velocity (cm/s)	6	7.7	9.4
Feed rate (g/s)	2.6	3.8	5
Length (cm)	46	69	92

Table 2: Charge per mass ration (Q/m) of ABS and HIPS granules, for the 17 runs of the composite experimental design

N°	Velocity v [cm/s]	Feed rate ϕ [g/s]	Tray length L [cm]	Charge/masse ABS Q/m [nC/g]	Charge/masse HIPS Q/m [nC/g]
1	6	2.6	46	1.097	-1.345
2	9.4	2.6	46	0.816	-0.646
3	6	5	46	0.947	-0.860
4	9.4	5	46	0.805	-0.777
5	6	2.6	92	1.116	-1.687
6	9.4	2.6	92	1.241	-1.496
7	6	5	92	1.324	-1.827
8	9.4	5	92	1.062	-1.123
9	6	3.8	69	1.153	-1.04
10	9.4	3.8	69	1.226	-1.166
11	7.7	2.6	69	1.202	-1.58
12	7.7	5	69	1.141	-0.971
13	7.7	3.8	46	1.055	-1.083
14	7.7	3.8	92	1.438	-1.649
15	7.7	3.8	69	1.188	-1.249
16	7.7	3.8	69	1.17	-1.33
17	7.7	3.8	69	1.201	-0.915

Table 3: Mathematical model of the charge per mass ratio obtained by MODDE.5.0

ABS Goodness of fit: $R^2 = 0.984$ Goodness of prediction: $Q^2 = 0.918$

$$Q/m = 1.17986 - 0.0381686v^* + 0.00409893\phi^* + 0.0789967L^* - 0.056774v^{*2} - 0.0226951\phi^{*2} + 0.0514158 v^*L^*$$

HIPS Goodness of fit: $R^2 = 0.984$ Goodness of prediction: $Q^2 = 0.902$

$$Q/m = -1.24331 - 0.00807782 v^* + 0.193884\phi^* - 0.106528L^* - 0.101326 v^{*2} - 0.0832048 L^{*2} + 0.0163175 v^*L^*$$

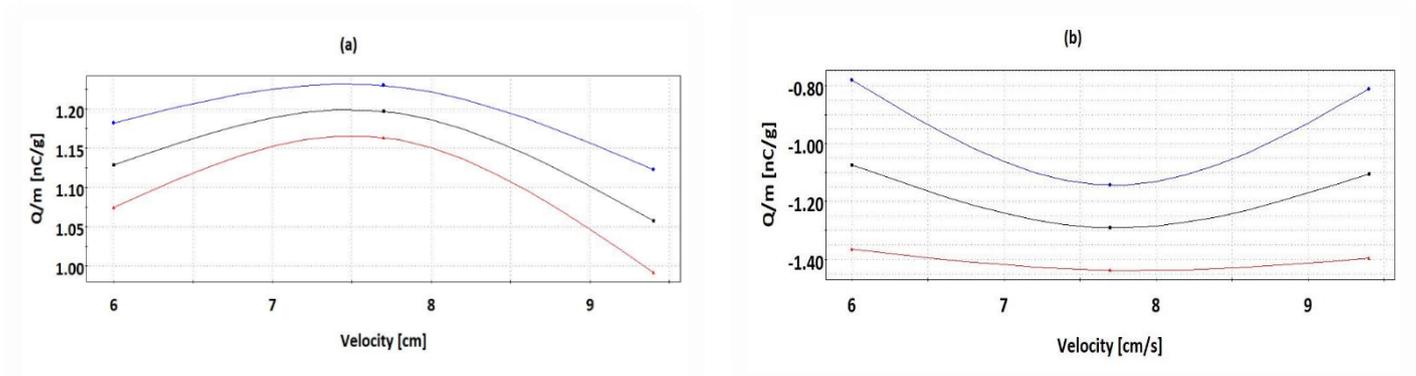


Fig.8. Modde 5.0 predicted variation on the charge per mass ratio as function of velocity, for (a) ABS and (b) HIPS. The other variables were maintained at the center of the experimental domain: $\phi=3.8$ g/s, $L=69$ cm. The upper and lower curves on graph indicate the limits of 95% confidence level interval.

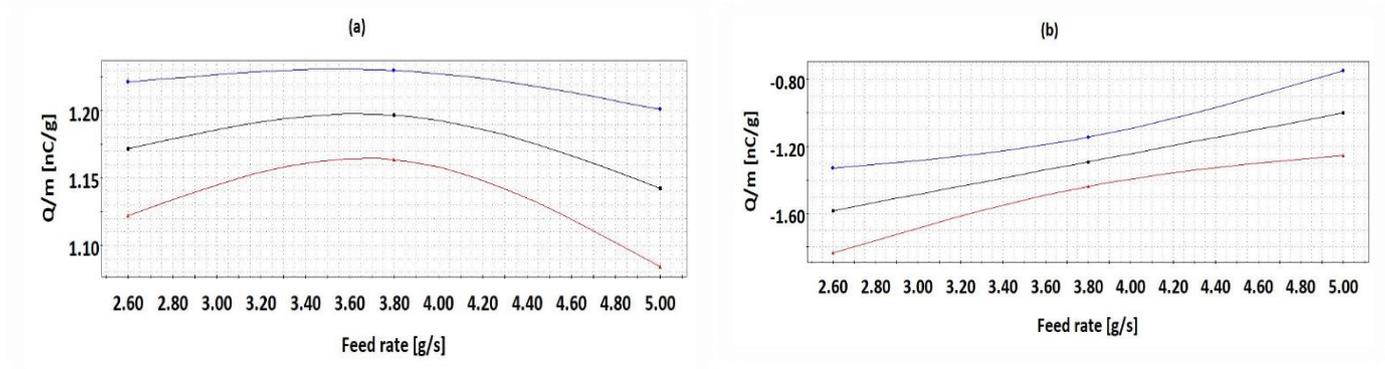


Fig.9. Modde 5.0 predicted variation of the charge to mass ratio as function of feed rate for (a) ABS and (b) HIPS. The other variables were maintained at the center of the experimental domain: $v=7.7$ cm/s, $L=69$ cm. The upper and lower curves on graph indicate the limits of 95% confidence level interval.

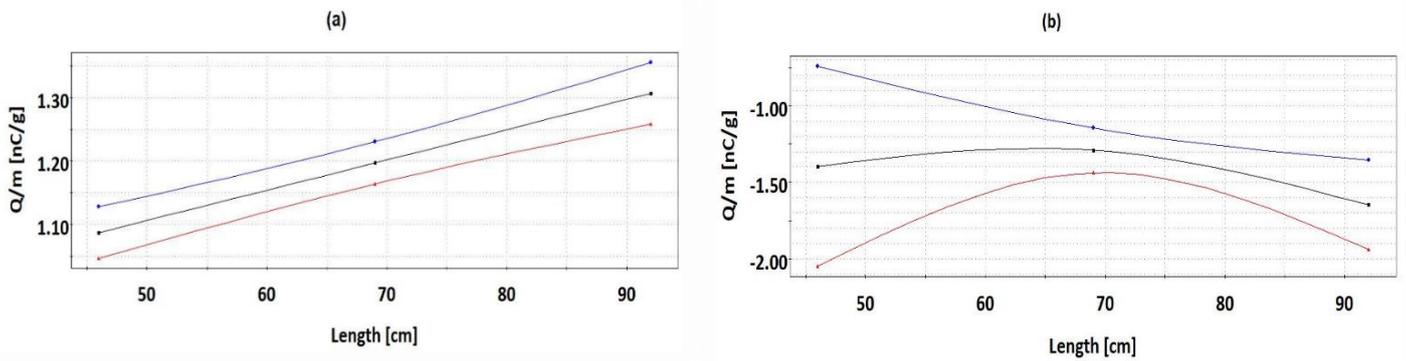


Fig.10. Modde 5.0 predicted variation of the charge per mass ratio as function length, for (a) ABS and (b) HIPS. The other variables were maintained at the center of the experimental domain: $v=7.7$ cm/s, $\phi=3.8$ g/s. The upper and lower curves on graph indicate the limits of 95% confidence level interval.

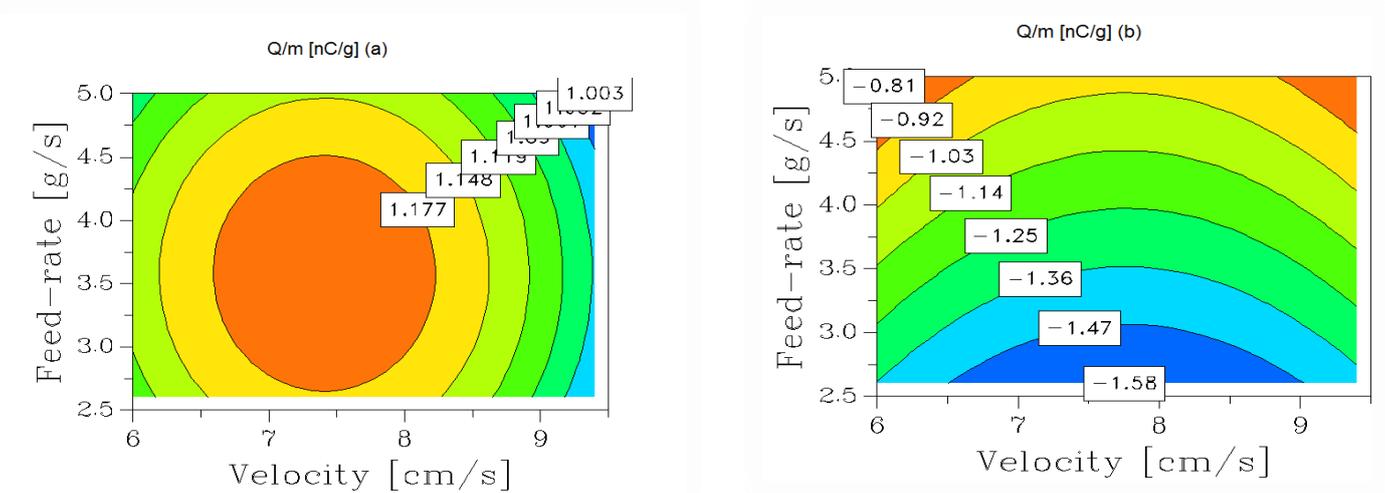


Fig.11 Contour plots of the response Q/m charge per mass ratio calculated with MODDE 5.0 for (a) ABS and (b) HIPS, (length $L=69$ cm).