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Behavior of insulating particles in an electrostatic separator associated with a new spiral-type tribocharger

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Abstract - Electrostatic separation processes are emerging as the solution of choice for recycling waste from end-of-life equipment in various industries. The separation of the different constituents of such plastic mixtures is the key to successful recycling. The main objective of this work was the development of a new spiral-type tribo-charging device with application in the field of electrostatic separation. The spiral charger offers a very high charging rate compared to other triboelectric systems. It favors collisions of the particles with the inner wall, which is very efficient to separate a mixture of ternary particles. The study was conducted with samples of various medium-sized (2-5 mm) granular plastics, for several values of air velocity, pipe length and particle mass in the turbocharging device. The spiral charger was associated with a belt-type electrostatic separator to process a granular insulating mixture, consisting of three types of plastic products Polyvinyl Chloride (PVC), Polypropylene (PP) and Polystyrene (PS). This work also aims at numerically simulating the dynamic behavior of insulating particles in belt-type electrostatic separators. The good separation obtained for this ternary mixture shows the efficiency of the new tribocharger.

Keywords - waste treatment; triboelectricity; particle charging; electric field; numerical simulation; electrostatic processes, particles trajectories

I. INTRODUCTION

The electrostatic separation technique is a process capable of satisfying the requirements of efficient management of plastic wastes. Indeed, landfill or incineration cannot be considered as effective end-of-life solutions for these materials, because of their negative ecological impact [1] – [3]. Electrostatic technologies are preferred to other methods because they are non-polluting, have low energy consumption and low operating and maintenance costs [4] – [6].

In recent years, electrostatic separation has been increasingly used for the recycling of industrial waste [7] – [9]. The principle of separation is based on Coulomb's force acting on charged insulating particles. The success of the separation depends on the amount of electric charge carried by the particles to be sorted in the electric field [10] – [12]. In the case of granular mixtures composed of insulating materials, the particles to be separated get electrically charged by using the triboelectric effect.

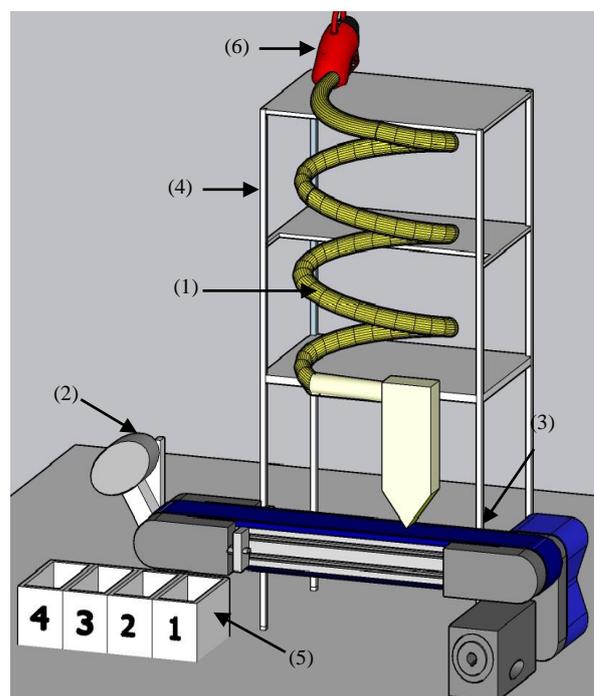


Fig. 1. Schematic representation of electrostatic separator with spiral-type tribocharger; 1. Spiral -type device; 2. Electrode (cylindrical; ellipse cross section; ellipse diameters: 120 mm and 60 mm); 3. Metal-belt conveyor connected to the ground (belt width: 100 mm; distance between the axis of the rolls: 1200 mm; roll radius: 80 mm; roll velocity: 15 rpm); 4. Metal frame; 5. Collector (4 boxes); 6. Blower.

Triboelectricity is an electrostatic phenomenon employed in various industrial processes and consists in the transfer of electrical charges when two different materials are rubbed against each other or simply brought into contact; one or more materials become positively charged, and the other(s) become negatively charged. The trajectories of the plastic particles are deflected in the electric field according to the polarity and the amount of their charge [10]-[13].

The main objective of this work was to study the efficiency of using a new spiral-type tribo-charger in association with a belt-type electrostatic separator (Fig. 1). This electrostatic separator has been the subject of previous studies, which identified its optimal operating conditions [14]-[18].

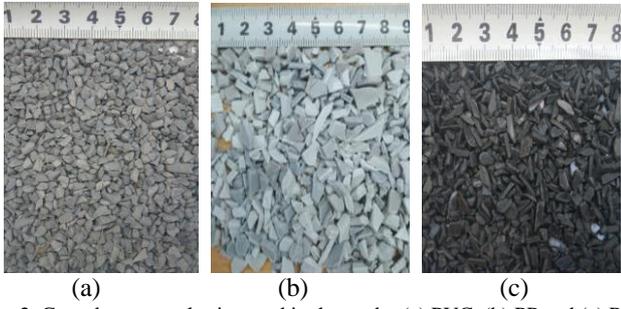


Fig. 2. Granular waste plastics used in the study: (a) PVC, (b) PP and (c) PS.

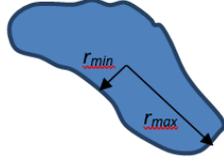


Fig. 3. Explanatory for the calculation of the characteristic size of the particles.

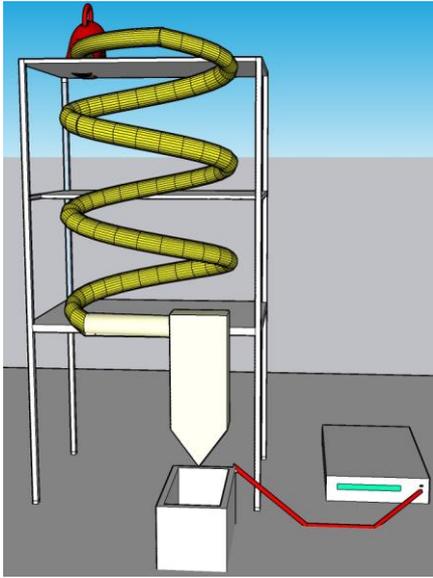


Fig. 4. Schematic representation of the device for measuring the acquired charge. (1) Electrometer; (2) Faraday pail

II. MATERIAL AND METHODS

The experiments were performed with granules originating from waste electric and electronic equipment (WEEE). Three types of granular plastic materials, with characteristic sizes between 2 mm and 5 mm, were used in the present study: Polypropylene (PP), Polyvinyl chloride (PVC) and Polystyrene (PS) (Fig. 2). The characteristic size was calculated with the formula:

$$r_{moy} = (r_{max} + r_{min})/2 \quad (1)$$

the significance of $r_{max} + r_{min}$ being given in Fig. 3.

The new spiral-type tribocharger for granular mixtures (Fig. 4) was conceived and built at the University of Sidi Bel Abbas, Algeria. The main part of the device is a PVC pipe of radius $R = 80$ mm and length $L = 5000$ mm or 2500 mm. The granular product to be triboelectrically charged was injected progressively into the pipe, by a blower, which was used to adjust the air velocity. The spiral shape of the pipe allows the increasing of the number of particle/wall collisions that produce the tribocharging effect, according to the relative positions of PVC, PP and PS in the triboelectric series. The turbulent nature of the flow prevents the particles having charges of opposite polarities to agglomerate.

The pipe ends in a special-designed cylindrical tube that minimizes the air velocity; this device can be considered as a mechanical flow regulator favorable to the electrostatic separation of granular mixtures. To facilitate the analysis of the experimental results, both this cylindrical tube and the hopper at the exit of it are made of the same material as the tribocharging pipe, PVC.

The metal frame (length 730 mm, width 500 mm, height 1480 mm) that serves as a support for the PVC pipe and the blower, is made of steel profiles, connected to the ground, to facilitate the dissipation of the charge that might accumulate on the various parts of the tribocharger.

The three factors considered for the triboelectric charging experiments were: the pipe length L , the voltage V that supplied the blower to adjust the air velocity, and the sample mass m . To measure the charge acquired by the granular products, an electrometer (model: Keithley 6514) connected to a Faraday pail was placed at the outlet of the spiral-type tribocharger (Fig. 4).

The triboelectric charging study consisted of quantifying the charge of PVC, PP and PS particles in the spiral-type tribocharger and then observing their behavior in the belt-type electrostatic separator.

The air velocity was the first factor to be studied, by adjusting the voltage V of the power supply of the blower to 40%, 60%, 80%, 100% of its maximum value. The ambient temperature and relative humidity had the following values: $T = 18.1^\circ\text{C}$ to 19°C , $RH = 39.2\%$ to 41% . The sample mass was the same for all the three types of products: $m = 10$ g.

A second series of experiments was carried out for four values of the mass m of product introduced into the charger: $m = 5$ g, 10 g, 15 g and 20 g, at a constant value of the air velocity, obtained for $V = 100\%$, and two pipe lengths $L = 5000$ mm and $L = 2500$ mm. The temperature was about 17.2°C to 18°C and the relative humidity of the ambient air was 44.5% to 45.1%.

The final series of experiments consisted in observing the behavior of each polymer in the belt-type electrostatic separator and testing the efficiency of the new triboelectric charger. The experiments were performed on an insulating granular mixture containing 1/3 of PVC, 1/3 of PP and 1/3 of PS. The significant difference in the charge acquired by the three polymers in the spiral-type tribocharges suggested the possibility of their separation. The triboelectric charging was performed with the long spiral-type device ($L = 5000$ mm), at maximum air velocity ($V = 100\%$) and for a mass $m = 30$ g (10 g of each product). Based on the results of preliminary experiments and numerical simulation of particle trajectories, the control variables of the belt-type separator were set as follows: rotation speed of belt drive roll, 15 rpm; inter-electrode distance $d = 5$ cm; applied high voltage $U = 35$ kV; angular position of the high-voltage electrode $\alpha = 45^\circ$.

III. RESULTS AND DISCUSSION

The values given in Table I and II are the averages of the results obtained in three tribocharging experiments conducted for various air velocities. The best charging rates were obtained with a length of 5000 mm. This can be explained by the increase of the contact surface and the number of collisions inside the pipe. For all three polymers, the highest charge rate was obtained when $V = 100\%$, as the air velocity increases the collision force between the particle and the inner wall of the pipe.

TABLE I. INFLUENCE OF AIR VELOCITY ON THE CHARGE PER MASS RATIO OF THREE POLYMERS IN THE SHORT SPIRAL-TYPE TRIBOCHARGER

Length (mm)	Mass (g)	Air velocity (%)	PVC	PP	PS
			Charge per mass (nC/g)		
2500	10	40	-0.81	0.09	8.26
		60	-1.12	0.12	9.25
		80	-1.76	0.17	12.74
		100	-2.8	0.18	13.67

TABLE II. INFLUENCE OF AIR VELOCITY ON THE CHARGE PER MASS RATIO OF THREE POLYMERS IN THE LONG SPIRAL-TYPE TRIBOCHARGER

Length (mm)	Mass (g)	Air velocity (%)	PVC	PP	PS
			Charge per mass (nC/g)		
5000	10	40	-1.78	0.19	14.21
		60	-1.94	0.23	17.65
		80	-2.47	0.24	20.3
		100	-4.3	0.28	21.39

TABLE III. INFLUENCE OF SAMPLE MASS ON THE CHARGE PER MASS RATIO OF THREE POLYMERS IN THE SHORT SPIRAL-TYPE TRIBOCHARGER

Length (mm)	Air velocity (%)	Mass (g)	PVC	PP	PS
			Charge per mass (nC/g)		
2500	100	5	-2.33	0.11	12.57
		10	-2.8	0.18	13.67
		15	-2.74	0.24	13.23
		20	-2.87	0.27	13.74

TABLE IV. INFLUENCE OF SAMPLE MASS ON THE CHARGE PER MASS RATIO OF THREE POLYMERS IN THE LONG SPIRAL-TYPE TRIBOCHARGER

Length (mm)	Air velocity (%)	Mass (g)	PVC	PP	PS
			Charge per mass (nC/g)		
5000	100	5	-3.52	0.3	20.14
		10	-4.3	0.28	21.39
		15	-3.92	0.4	20.83
		20	-4.13	0.38	21.18

The results of the second series of tribocharging experiments performed with different quantities of products introduced in the new device are summarized in Table III and IV. They show that the variation of the mass does not influence the value of the charge per mass ratio, as the tribocharging was mainly due to particle-wall collisions. As in the first series of experiments, the particles acquired a higher charge with the length 5000 mm device; the PS granules got positive charges and the PVC and PP particles acquired different levels of negative charges.

Figure 5 shows that the charge acquired by the PVC, PP and PS particles increases with of the velocity of the air flow injected at the inlet of the charger. For PP or PS particles, the increase in the length of the triboelectric charger generates an increase in the charge acquired by the increase in air flow. By keeping a constant flow rate at the charger inlet it was possible to avoid the particle / particle collisions that could have eventually influence the sign and the amount of the acquired charge.

The results of the electrostatic separation experiments are synthetically presented in Figs. 6 and 7. The PS granules were repelled by the positive electrode because they have the same sign and fall into the box 1 (Fig. 1). The lower positive charge acquired by the PP granules as compared to that of the PS granules made them fall into the box 2 of the collector. The negatively charged PVC granules are attracted by the high-voltage electrode and fall into the boxes 3 and 4.

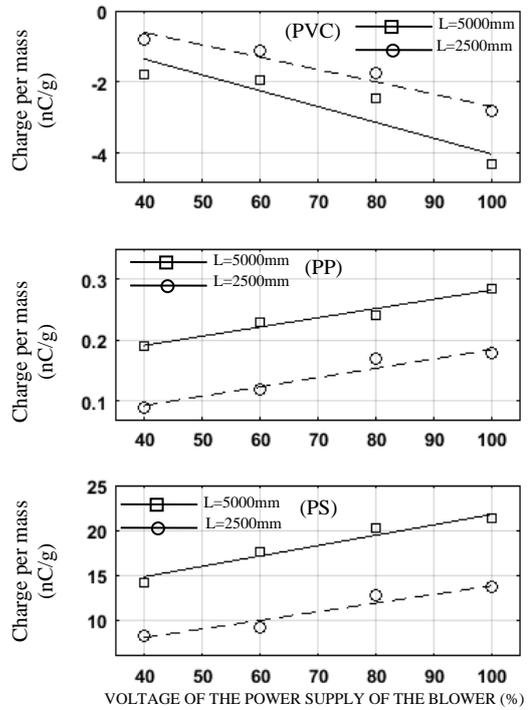


Fig. 5. Influence of the voltage of the power supply of the blower [%] on the charge per mass ratio for three polymers.

TABLE V. CHARGE AND MASS DISTRIBUTION AFTER SEPARATION IN EACH BOX.

	Box1	Box2	Box3	Box4	
PS	$M(g)$	8.6000	0.7000	0	0
	$Q/m(nC/g)$	23.1650	-0.4171	0	0
	$Q/m(nC/g)$	21,3900	0	0	0
PP	$M(g)$	0,3000	9,7000	0,1000	0
	$Q/m(nC/g)$	23.1650	-0.4171	-0.7521	0
	$Q/m(nC/g)$	0	0.2800	0	0
PVC	$M(g)$	0	1.7000	4.8000	3.5000
	$Q/m(nC/g)$	0	-0.4171	-0.7521	-11.0516
	$Q/m(nC/g)$	0	0	-4.3000	0

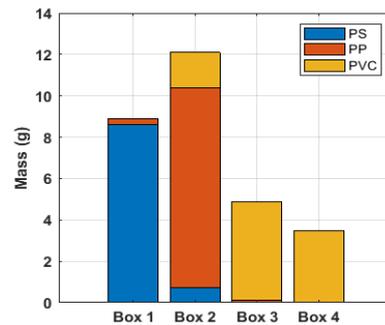


Fig. 6. The mass of the products (PVC, PP and PS) recovered in each box (total mass: 30 g; applied high-voltage: 35 kV; belt roll speed: 15 rpm).

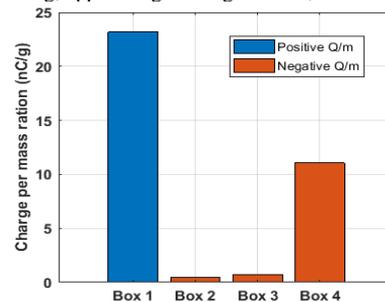


Fig.7 Charge per mass ratio of the mixtures of particles recovered in each box.

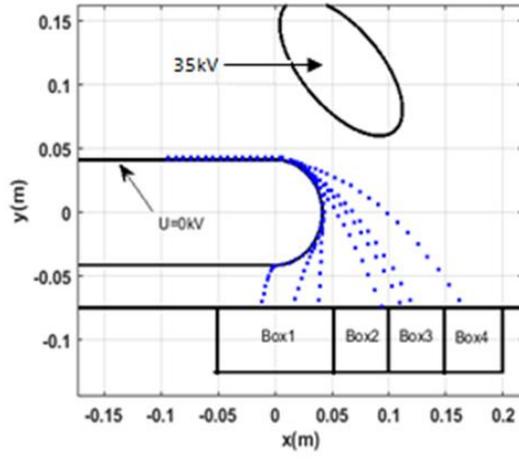


Fig. 8. Examples of particles trajectories calculated with the numerical model adopted for the present study.

Fig. 6 shows the dispersion of particles of each of the three polymers in the four boxes of the collector. The charge per mass ratio of the mixtures of particles recovered in each box is given in Fig. 7.

The results of the electrostatic separation experiments can be used for evaluating the efficiency of the tribocharging, by determining the charge per mass ratio for the particles of each polymer recovered in a given box of the collector. This was done by using a numerical simulation algorithm based on a standard model for the calculation of particle trajectories. The model considered the electrical, gravitational, centrifugal and aerodynamical forces exerted on particles assumed of spherical shape; it made use of the equations of motion described in several previous papers [19]-[22]. Some examples of simulation results obtained with the numerical particle trajectory model adopted in the present paper are displayed in Fig. 8.

At the first step, the algorithm calculated such separation trajectories for 30,000 particles: 10,000 PS particles (mass density: 1,050 kg/m³), 10,000 PP particles (mass density: 950 kg/m³), and 10,000 PVC particles (mass density: 1,200 kg/m³). For each of the three sets of 10,000 particles, the radii were uniformly distributed between 0.5 and 5 mm. Surface charge densities ranging between -27 μC/m² and +27 μC/m² (limits imposed by the dielectric strength of ambient air) were randomly attributed to each particle. Retained for further calculations were only the trajectories of the particles having realistic values of the charge per mass ratio, in the range ±30 nC/g, which was chosen slightly wider than what was found in the experiments carried out with plastic particles of mm size [4], [10], [13].

For each PS, PP, and PVC particle, the simulation program calculated its trajectory and determined its final position in one of the boxes of the collector. These positions were recorded in a data base, which also contained the radius, mass and charge per mass ratio of each particle.

The next step of the algorithm used these data to select a group of particles that would give the same distributions of mass and charge/mass in the boxes of the collector as the ones experimentally obtained. For each box $k = 1 \dots 4$, a number N_{ki} of particles of was initially chosen for each polymer $i \in \{\text{PS, PP, PVC}\}$ using the formula:

$$N_{ki} = M_{ki} / m_i \quad (2)$$

where M_{ki} is the mass of the particles of polymer i in box k , and m_i is the average mass of a particle of polymer i .

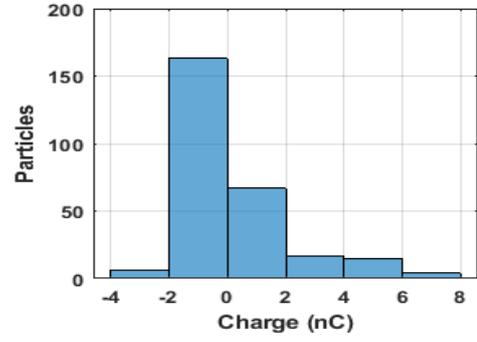


Fig. 9 Charge distribution of selected particles.

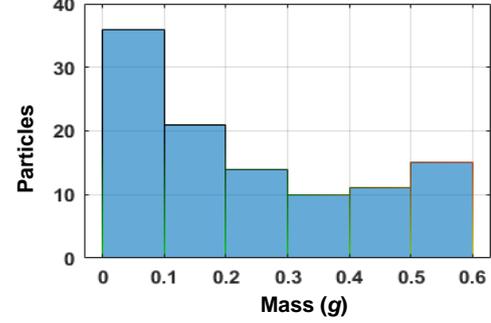


Fig. 10. Mass distribution of selected particles.

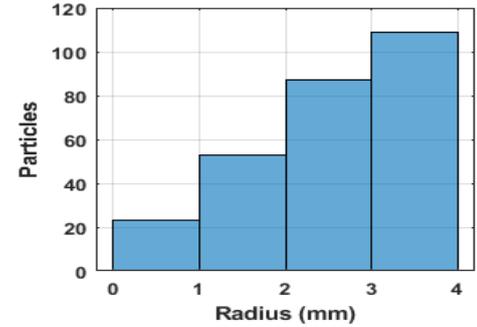


Fig. 11. Particle size distribution of selected particles.

If the mass M_{ks} of the $N_k = N_{kPS} + N_{kPP} + N_{kPVC}$ simulated particles selected for box k was lower than the mass $M_k = M_{kPS} + M_{kPP} + M_{kPVC}$ of the product collected in box k , a particle was added to the group. If the charge $Q_{ks} = Q_{ksPS} + Q_{ksPP} + Q_{ksPVC}$ of the simulated particles was lower than the measured charge Q_k of the particles collected in box k , the charge of the added particle was higher than the average of those already selected. Otherwise, it should be lower.

If the mass M_{ks} of the selected particles was higher than the measured one M_k , a particle was removed from the group. If the charge of the particles in the group Q_{ks} was lower than the measured one Q_k , the removed particle was the one having the lower charge. Otherwise, it was the one having the higher charge.

The iterative process continued till:

$$|[(Q_{ks}/M_{ks}) - (Q_k/M_k)] / (Q_k/M_k)| < 0.002 \quad (3)$$

i.e., the absolute error between the simulated and measured charge per mass ratios for the box k was less than a fixed value, for instance: 0.2%.

The distribution of charge, mass and size of 272 particles selected using this algorithm described above (89 PS; 90 PP; 93 PVC) are represented respectively in figures 9, 10 and 11. The distribution of the mass and charge per mass ratio of the selected particles in the 4 boxes is identical to that of the real particles (Figs. 12 and 13).

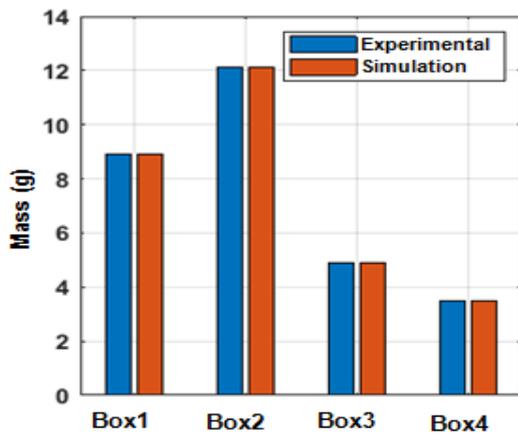


Fig. 12. Experimental and simulated mass of the products recovered in the four boxes of the collector.

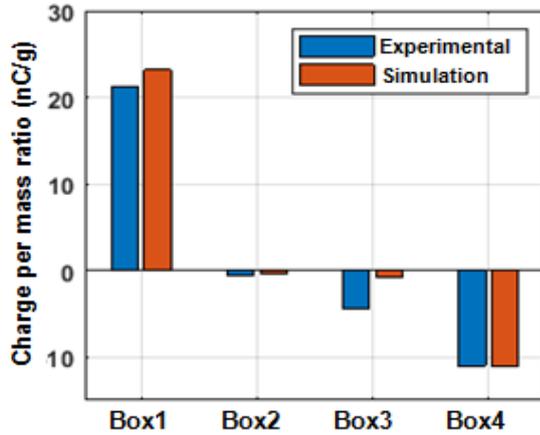


Fig. 13. Experimental and simulated charge per mass ratio of the products recovered in the four boxes of the collector.

The group of 272 selected particles having mass and charge characteristics identical to the group of particles used in the experimental study, it can be used in the analysis of the charge distribution of the particles that were subjected to the electrostatic separation process recovered, which is the charge they acquired in the triboelectric charger. In this way, it is possible to evaluate the efficiency of this device in charging the various sorts of particles.

The distributions of the charge of the 89 PS, 90 PP, and 93 PVC particles used in the simulation are represented in Figs. 14 to 16. The majority of the PS particles (more than 90 %) have a positive charge varying up to 8 nC (Fig. 14). The rest of the particles (less than 10 %) have a negative charge in the range -2 nC to 0 nC. In the PP case (Fig. 15), more than 70 % the particles have a negative charge of less than 2 nC in absolute value, and less than 30 % have a positive charge lower than 2 nC. All PVC particles (Fig. 16) have negative charges ranging between -4 nC and 0 nC.

This analysis shows the ability of PS PP and PVC materials to acquire different electrical charges in the new tribocharger. It also enables the quantification of these charges, which could not be deducted based only on the measurements performed with the Faraday pail.

IV. CONCLUSIONS

The experiments described in this article illustrate the efficiency of the new triboelectric charging device; they prove that it can provide an excellent separation and ensure the quality of the recycled plastics.

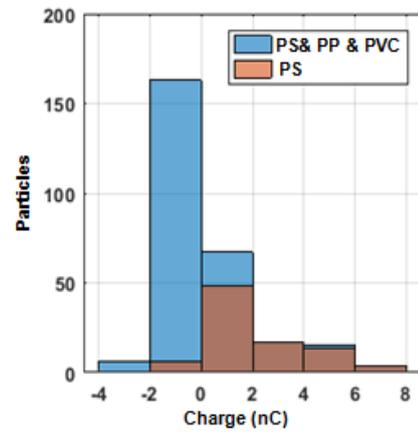


Fig. 14. Charge distribution of PS particles.

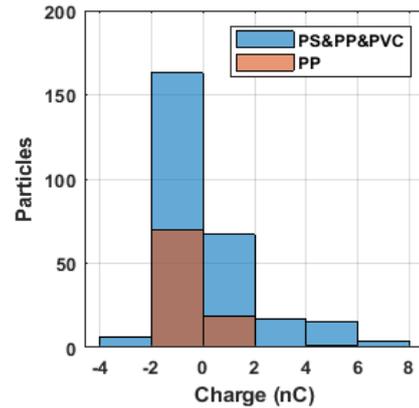


Fig. 15. Charge distribution of PP particles.

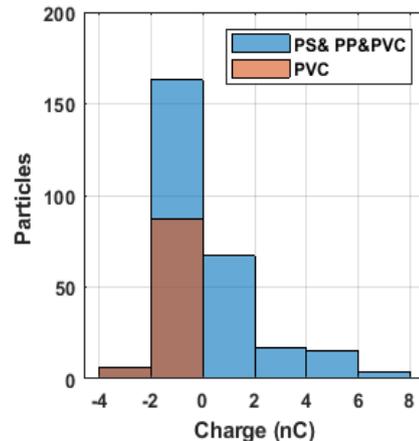


Fig. 16. Charge distribution of PVC particles.

1) The performance of the triboelectric charging process depends essentially on the air velocity and the length of the pipe.

2) The mass of the samples does not have a significant influence on the charge/mass of the tribocharged polymers.

3) The new tribocharger can be adapted to any electrostatic separator and facilitates the continuous separation.

4) The spiral-type tribocharger can be successfully used for the electrostatic separation of ternary mixture of plastics (PVC, PP and PS).

5) The comparison between experimental and simulation results of the particle trajectory can predict the particle behavior with a good precision and reduces the number of preliminary experiments.

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