Recent Researches in Electrostatic Separation Technologies for the Recycling of Waste Electric and Electronic Equipment

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1. INTRODUCTION

A Circular Economy Action Plan was adopted by the EU Commission in December 2015 with the aim to boost the economic growth and investments, to develop a resource-efficient and competitive economy. But, on average, recycled materials only meet less than 12 % of the EU demand for materials [1]. In order to increase the confidence in secondary raw materials the recycling industry must be able to deliver high-quality materials, particularly in the case of complex end-of-life products containing critical materials as waste of electric and electronic equipment (WEEE). This is currently considered to be one of the fastest growing waste streams in the EU, growing at 3-5 % per year. These complex end-of-life products offers substantial opportunities in terms of secondary raw materials available on the market.

Electrostatic separation technologies are clean and environmentally friendly, characterized by low energy consumption, simplicity, and moderate cost maintenance [1-3]. They are increasingly used to recover metals and plastics from WEEE or to separate plastic mixtures by polymer type.

The paper presents some recent results obtained at the Technical University of Cluj-Napoca and the University of Poitiers in the field of corona-electrostatic and tribo-electrostatic separation of granular materials originating from WEEE.

2. CORONA-ELECTROSTATIC SEPARATION

2.1. Principle of the Corona-electrostatic Separation

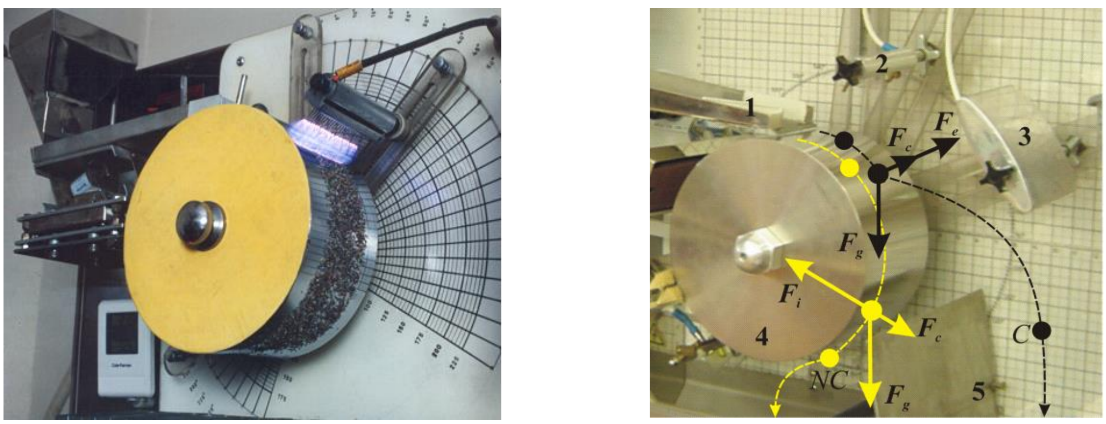
Corona-electrostatic separation is the selective sorting of conductive and non-conductive granules under the action of a space-charge electric field [2]. The established equipment in this technology is the roll-type corona-electrostatic separator, where the granular mixture to be separated is fed on the surface of a rotating metallic roll, connected to the ground (Fig. 1). A space-charge electric field is generated between this grounded electrode and an active electrode connected to a high-voltage supply (Fig. 1.a) [4, 5].

The insulating particles are charged in the corona field and then pinned to the surface of the rotating roll by the electric image force F_i [6]. They are detached from the roll surface in the neutralizing electrode zone or by a wiper brush and are collected on the left side of the splitter.

The conductive particles charge by electrostatic induction when in contact with the roll electrode and are attracted to the high-voltage electrode by the electric field force F_e [4]. Under the action of this force and the centrifugal force F_c they detach from the roll surface and are collected on the right side of the splitter. Consequently, the factors influencing the separation process should include the high-voltage level, the electrode configuration, the feed rate, the granule size, and the roll speed [5].

2.2. Improved Recovery of Copper from Automotive Electric Cable Waste

Electric wires represent a significant part of the electric and electronic wastes, so it is important to find efficient and reliable solutions to recycle them. Physical dissociation of the conductor (copper) and the insulator (PVC) is necessary in many technologies aimed at recovering these two components. Vibrating tables are frequently employed to separate copper and PVC, but the recovery of copper could be improved to a greater degree as it does not reach 100% at this time.



(a) (b)

FIGURE 1. (a) Plastic granules pinned on the roll surface by a positive corona discharge obtained from a needle-type corona electrode. (b) Forces acting on conducting (C) and non-conducting (NC) particles in roll-type corona-electrostatic separators: F_e: electric field force; F_i: electric image force; F_c: centrifugal force; F_g: gravitational force; 1: vibratory feeder; 2: corona electrode; 3: electrostatic electrode; 4: grounded roll electrode; 5: splitter. [5]

Corona-electrostatic separation technology can be successfully used to improve the copper recovery from electric cable waste originating from the automotive industry. The separation experiments were performed with a fine polyvinyl chloride and copper granular mixture obtained as “PVC fraction” in the recycling process of electric cable waste from automotive industry.

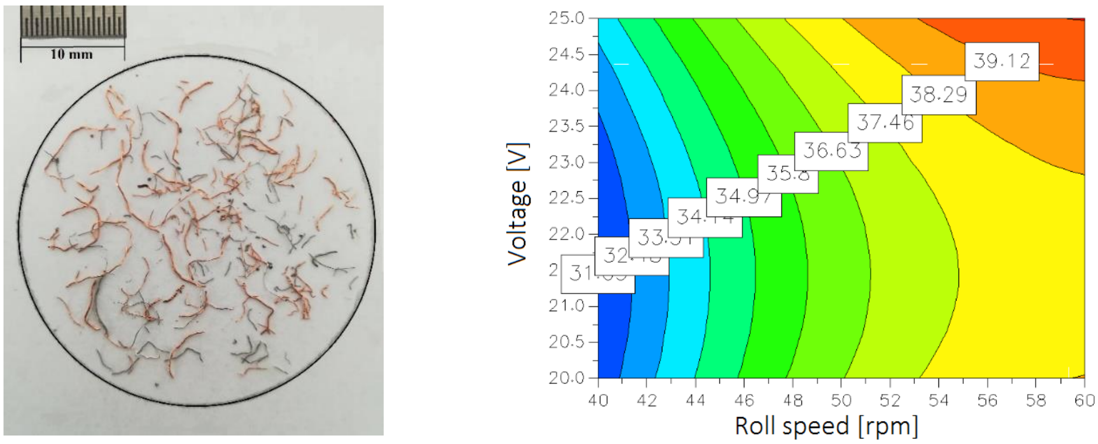
The design of experiments method was used to establish the parameters of the electrostatic separation process leading to a maximum recovery of copper. In accordance with this methodology [7] the high voltage level U and the roll electrode speed n was considered as control variables and the relative mass of the conductive fraction (Cu) was the process output

$$C_{fraction} = \text{conductive fraction mass / sample mass.}$$

The experimental results were analyzed by MODDE 5.0, a commercial program for the generation and evaluation of statistical experimental designs [8]. In accordance with this method the two control factors were varied over a set of 11 planned experiments, the results of which enabled the derivation of a quadric polynomial model.

A first set of 11 separation experiments was performed with the -0.63 mm granular size class. The conductive fraction purity obtained was as high as 99.8%, fully corresponding to the recycling industry requirements (Fig. 2.a). The predicted contour plots of the $C_{fraction}$ (Fig. 2.b) show that the maximum conductive fraction can be obtained at the maximum values of the input parameters U = 25 kV and n = 60 rpm. At lower values, the mass of the conductive fraction was lower because the electric field intensity as well as the centrifugal force decreased. For these reasons the conductive granules were deviated less than in the case of the high values of the input parameters.

The – 0.63 mm size class contained the majority of the copper that can be recovered with high purity. Up to 12.52 % of the raw PVC/Cu mixture can be recovered as copper (Fig. 3) by electrostatic separation of this size class. The conductive fraction obtained from the +0.63 mm size class represents no more than 1.34 % of the feeding material (Fig. 3) but with 70 % copper purity. The recovery rate of copper obtained by electrostatic separation of the initial “PVC fraction” could be as high as 95.86 %, increasing the overall copper recovery rate close to 100%.



(a) (b)

FIGURE 2. (a) Conductive fraction obtained by electrostatic separation of the -0.63 mm granular size. (b) Computed response contour plot of the relative mass of conductive fraction $C_{fraction}$ for the - 0.63 mm granular size class, with high-voltage and roll speed as variables.

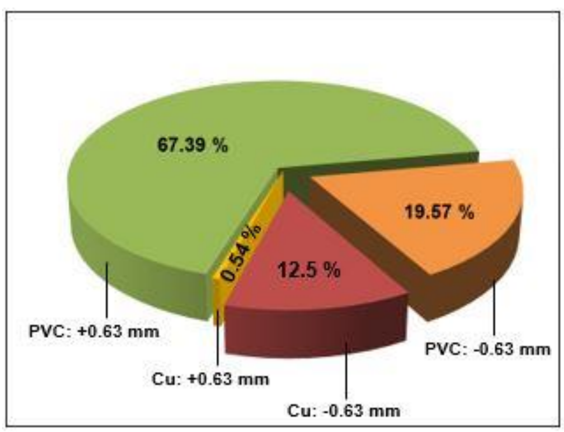


FIGURE 3. PVC and Cu content of the two granular size classes of the granular mixture.

2.3. Glass and Plastic Removal for Metal Concentration from WEEE

The main components of WEEE, almost half of the total weight, are iron and steel, followed by plastics which represent approximately 21%. Non-ferrous metals including precious metals, copper and aluminium represent approximately 13% while glass around 5% of the total weight of WEEE. After manual or automatic dismantling, the shredding process represents one of the most important steps in WEEE recycling. Magnetic separation technologies are used to recover ferrous components, then, corona-electrostatic separation can be employed to recover the non-ferrous metals (Cu and Al) from the mixture containing also glass and different type of plastics.

The granular mixture provided by a Romanian WEEE recycler was subjected to a size classification, then each granular size was fed in the corona-electrostatic separator in order to remove the plastic and glass granules and to concentrate the metals. The fine fraction (– 1 mm) contains about 79% metals, mainly copper wires, and 21% glass granules (Fig. 4.a).

The conductive granules of the middle size fraction (1 – 2) mm consist, mainly, of stranded copper and aluminium, while non-conductive granules consist of glass and plastics (Fig. 4.b). The coarse fraction contains over 90% aluminium and brass granules, but plastic granules as well (Fig. 4.c). Overall, the corona-electrostatic separation is able to improve the purity of this mixture originated from WEEE to almost 100 % metals by removing glass and plastic granules representing 15% of the initial material. Eddy-currents technology could be applied after the corona-electrostatic treatment of the granular mixture to separate copper and aluminium granules.

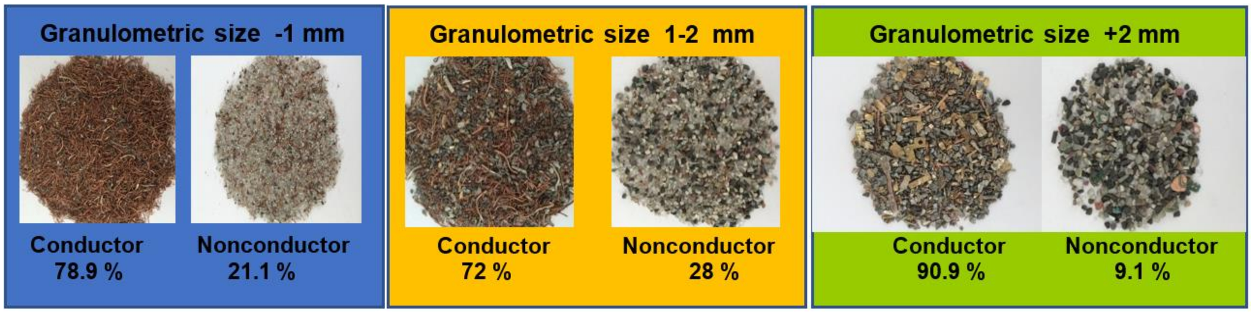
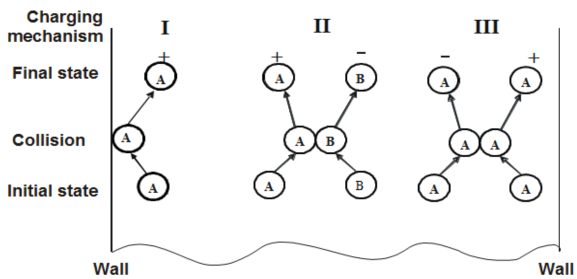


FIGURE 4. Results of the corona-electrostatic separation of the Cu/Al/glass/plastic mixture.

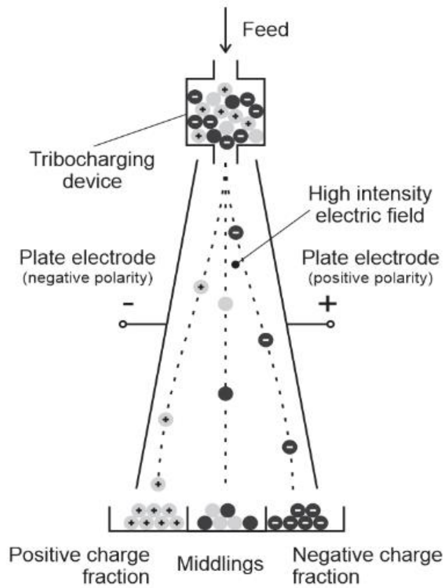
3. TRIBOELECTROSTATIC SEPARATION

3.1. Principle of the Triboelectrostatic Separation

In a triboelectrostatic separator the plastic granules acquire electric charge of opposite sign under the tribo-electric effect in the tribocharging device (Fig. 5.a) [9-16]. The charged granules are fed in a free-fall electrostatic separator where, in the high intensity electric field zone generated by two high-voltage electrodes, they are driven in opposite directions and are collected as distinct products (Fig. 5.b). Intensive researche has been carried out to improve the efficiency of the tribcharging technologies, which make use of vibrating or cyclone-like tribocharging devices.



(a)

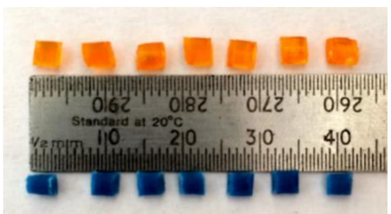


(b)

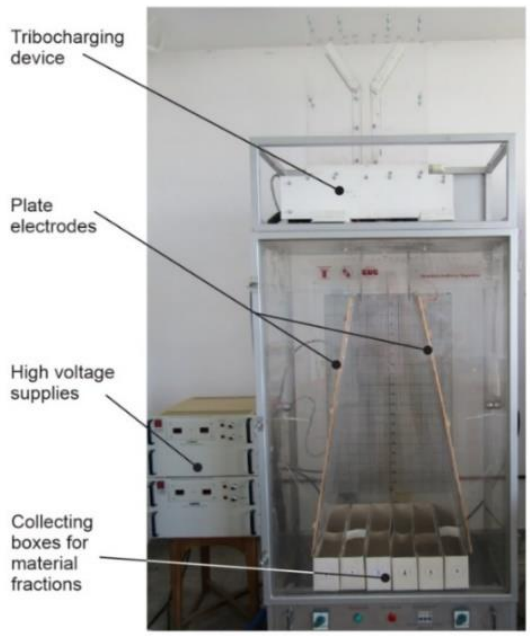
FIGURE 5. (a) Tribocharging mechanisms for plastic granules; (b) Free-fall triboelectrostatic separator.

3.2. Improvement of the Fluidized Bed Tribocharging Device for Electrostatic Separation of Plastics

The fluidized bed represents one of the most efficient solution for granules charge in tribo-electrostatic separation. The shape of the tribocharging chamber, the fluidizing air flow rate and the mass of granular material in the tribocharging device represent key factors in increasing the granules charge and in improving the efficiency of the tribo-electrostatic separation of plastic mixtures. The tribocharging and separation experiments were performed with virgin polyamide (PA) and polycarbonate (PC) granules (Fig. 6.a). All the granular samples used for separation experiments (Fig. 6.b) consisted of a mixture of 50% PA and 50% PC by mass. The analysis of the experimental results highlights that the charging process of the granules in fluidized bed has greater efficiency if the section area of the tribocharging chamber is constant, leading to a constant speed of the fluidizing air (Fig. 7.a).

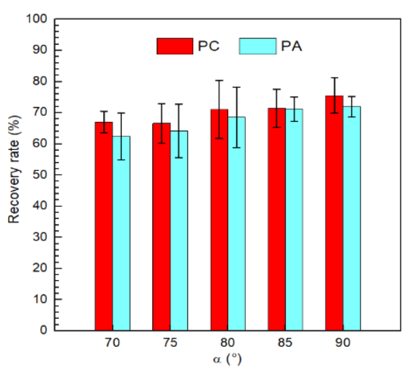


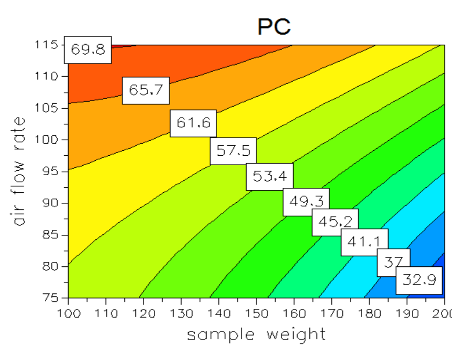
Material	Polyamide (PA)	Polycarbonate (PC)
Color	blue	orange
Shape	cylindrical	cylindrical
Size (mm)	ø 2.5 x 3.4	ø 3 x 3.6
Weight (mg)	20	22
Density (kg/m3)	1100	1200



(a) (b)

FIGURE 6. (a) Shape, dimensions, and characteristics of PA and PC granules.
(b) The free fall electrostatic separator equipped with the splayed air chamber of the tribocharging device.





(a) (b)

FIGURE 7. (a) Recovery rate of PC and PA as a function of angle α between the horizontal axis and the tribocharging chamber wall. (b) Predicted contour plots for the recovery rate of PC versus the sample weight (g) and fluidization air flow rate (m^3/h) [15].

A design of experiments (DOE) quadratic response surface model was used to study the influence of the sample mass and the air flow rate over the tribocharging process, taking the recovery rate of each material as the results. The granules charge obtained in the fluidized bed tribocharging device increases with fluidizing air speed which conducts to greater impact energies between granules. A lower volume density of granules in the tribocharging chamber, as well as a higher fluidizing air speed favor the charging process by increasing the kinetic energy accumulated by granules after successive collisions (Fig. 7.b).The granules charge in fluidized bed tribocharging devices increases with the number of collisions but in a greater measure with the impact energy between granules.

3.3. Triboelectrostatic Separation of Granular Mixtures

A free-fall triboelectrostatic separator was used for the separation of two particular mixtures of plastic waste from WEEE (Fig. 8). This experimental set-up contains in addition to the separator two high-voltage supplies connected to the separator electrodes, a turbo blower that generates the fluidized air with variable flow-rate for the tribocharging device, a heater and a steam generator for the fluidized air conditioning. The mixture of waste ABS and HIPS, can be efficiently separated in a single stage triboelectrostatic separation (Fig. 9). The purity of the two fractions is as high as 99.5% and the recovery rate is above 90%. More than two components of the granular mixture require a more complex separation flow. A four plastic waste mixture, ABS, HIPS, PC and PET can also be separated by a five stage triboelectrostatic separation (Fig. 10). The purity of the four separation products remains higher than 99% but the recovery rate diminishes to the values between 41% for PET and 90% for HIPS.

FIGURE 8. Experimental set-up of the laboratory free-fall triboelectrostatic separator used for plastic waste separation.

These results show that the triboelectrostatic separation can be successfully employed for the selective sorting of plastic waste mixtures originated from WEEE. High purity separation fractions can be obtained by this technology, but the recovery rate diminishes when the number of components increases, requiring more complex separation flows.

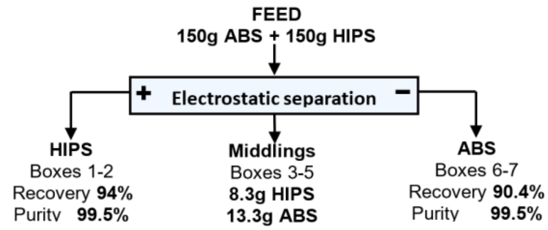


FIGURE 9. Single stage triboelectrostatic separation flow sheet of ABS/HIPS plastic waste.

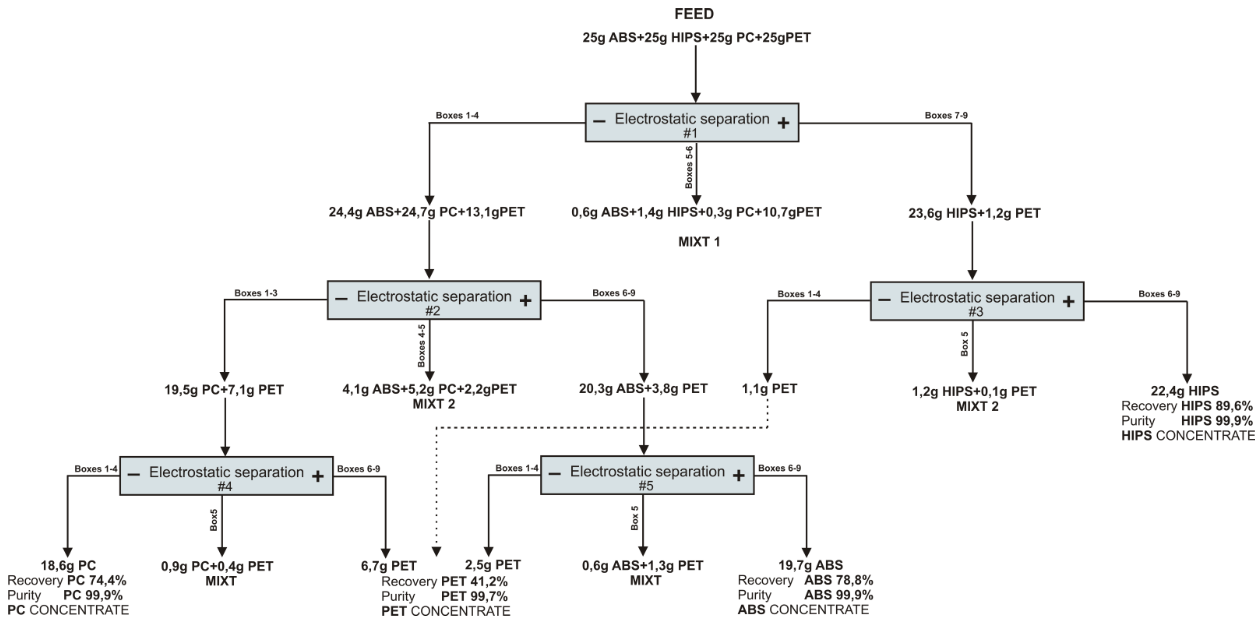


FIGURE 10. Five-stage triboelectrostatic separation of ABS, HIPS, PC and PET plastic waste.

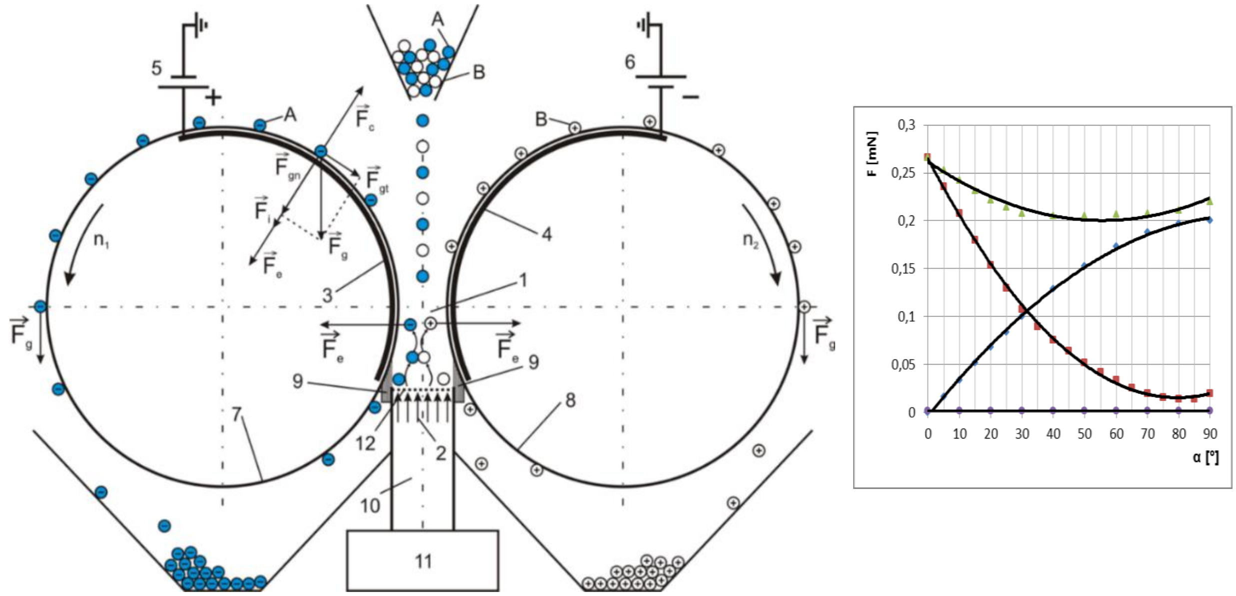
4. CONTINUOUS OPERATION TRIBOELECTROSTATIC SEPARATOR

An improvement of the classical “two-step” solution for the triboelectrostatic separation is to charge and separate the granules within the same device [17-19]. In this “single step” solution a fluidized-bed tribocharging process takes place in the same chamber and is simultaneous with the separation process.

4.1. Fluidized-bed Two-insulated-rolls-type Tribo-aero-electrostatic Separator

In this tribo-electrostatic separator the granular mixture (components A and B) is introduced in the tribocharging chamber (1) where, by the action of the air flow (2), the granules are maintained in a fluidized state and get charged by multiple collisions between each other (Fig. 11.a).

A high intensity electric field is generated in the tribocharging chamber zone by two circular-sector type electrodes (3, 4), that drives the charged granules in opposite directions. The granules are pinned on the surface of the rotating insulated rolls by the electric field force F_e, the electric image force F_i and the normal component of the gravitational force F_{gn}. Then the granules rotate with the rolls, exit the electric field zone, and detach from the rolls surface under the action of the gravitational force F_g or of the brushes (9) to be collected as separated fractions A and B. Insufficiently charged granules exit the tribocharging chamber at the opposite end with respect to the feeding and are collected as a third, enabling a continuous material flow. A charged granule pinned on the insulated roll surface keeps the charge acquired in the tribocharging process, so that the electric image force F_i is constant and the electric field force F_e is proportional with the electric field strength E. The electric field E and the electric field force F_e diminish with angle α but F_{gn} is increasing with α. In consequence, the pinning force $F_n = F_e + F_i + F_{gn}$ is almost constant (Fig. 11.b).



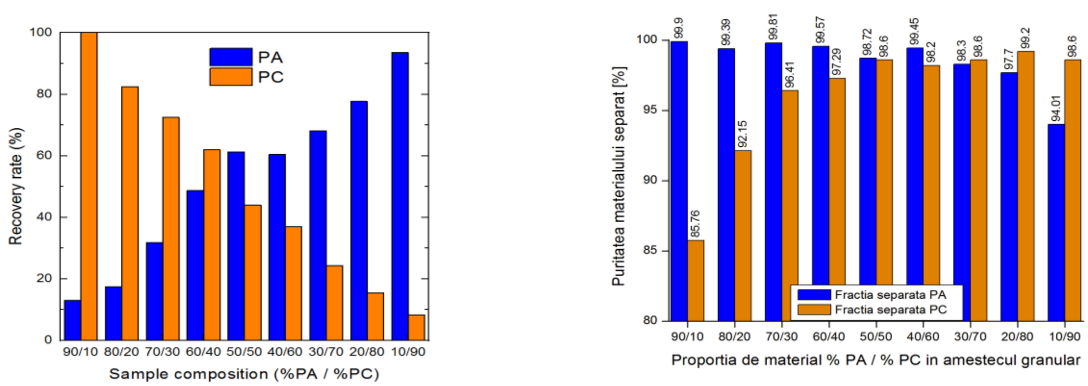
(a) (b)

FIGURE 11. (a) Tribo-electrostatic separator with fluidized bed and rotating rolls: 1 – tribocharging chamber, 2 – fluidizing air, 3, 4 – positive and negative electrodes, 5, 6 – positive and negative HV supplies, 7, 8, – rotating insulated rolls, 9 – sealing wiper brush, 10 – fluidization chamber, 11 – air supply with air flow control, 12 – filter. (b) Evolution of the forces acting on a charged granule pinned on the surface of the insulated roll versus granule position α. The granule mass was considered 20 mg and the charge 0.2 nC. The electric field strength was calculated for ± 20 kV high voltage level. [17]

4.2. Separation Experiments with Granular Mixtures in Varying Proportions

The aim of these experiments was to analyze the separation efficiency of the fluidized-bed two-insulated-rolls-type tribo-aero-electrostatic separator at different proportions of the mixture components. The samples weighing a total of 450 g were composed of PA and PC in different proportions, with 10% increments.

The experimental results put in evidence that the charge accumulated by the granules in the tribocharging process has a crucial influence on the separation efficiency. For unbalanced mixtures, where one of the materials is clear in minority the tribocharging process is very efficient for this component and less efficient for the majority component. So, the recovery rate of the minority component is very high (over 90%) and the recovery rate of the majority component is very low (around 10 %) in both cases (Fig. 12.a).



(a) (b)

FIGURE 12. (a) Analysis of the PA/PC separation efficiency on the fluidized-bed two-insulated-rolls-type tribo-aero-electrostatic separator. (a) Recovery rate of PA and PC. (b) Purity of PA and PC fractions.

On the other hand, as the composition of the sample gets more and more balanced, the recovery rate of the material in minority decreases as its proportion in the sample increases and the recovery rate of the material in majority increases as its proportion decreases.

Fig. 12.b shows a slight decrease in purity of both PA and PC fractions when its weight in the mixture decrease. This is because in the fluidized bed tribocharging process, granules of the majority component acquire charge of the same sign as the minority component and contaminate that fraction. Taking into account both recovery rate and purity of the separation fractions, the best results are obtained for balanced mixtures. The solution for unbalanced mixtures consists in successive separations with the recovery of the high purity fraction - the majority component and re-treatment of the insufficiently charged granules and low purity fraction - the minority component. After each separation the granular mixture will approach a balanced one.

4.3. The effect of Charged Granule Agglomerations on the Electric Field Distribution

The experimental analysis of plastic granules separation in the fluidized-bed two-insulated-rolls-type tribo-aero-electrostatic separator shows charged granules agglomerated in the zone of opposite sign electrode, modifying the electric field distribution and influencing the separation process. In order to evaluate the effect of these charged granules on the field distribution two 2D geometries were modelled. Figure 13.a shows the field distribution for the case of seven granules in one row, at 40 kV voltage drops and three charge densities.

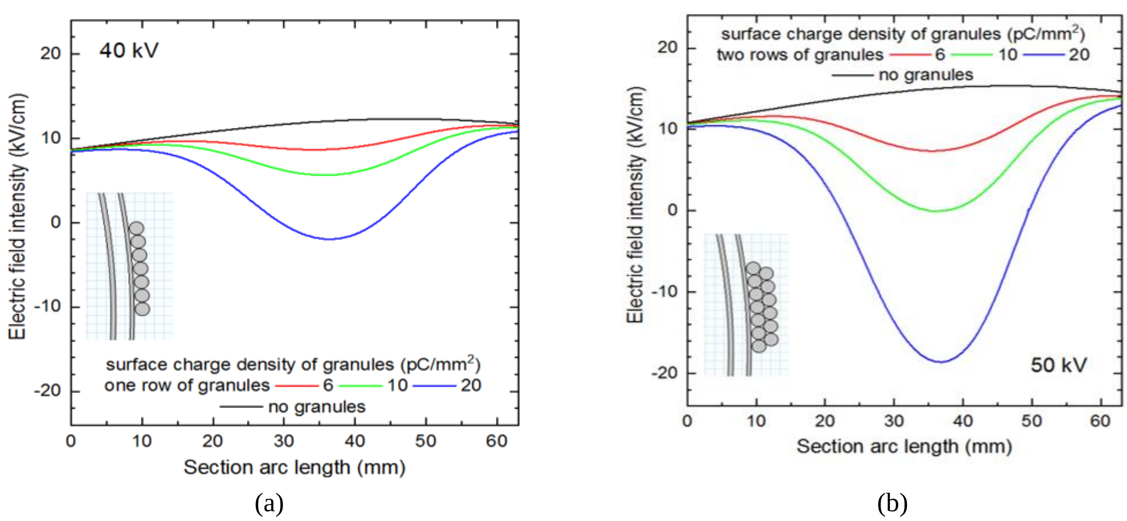


FIGURE 13. Electric field distribution along the symmetry line for one row of particles at a voltage drop of 40 kV (a) and for two rows of particles at a voltage drop of 50 kV (b) [20].

The decrease of the field is more pronounced for a higher charge value. If the superficial charge is as high as 20 pC/mm^2, an electric field of 2 kV/cm maximum intensity and reversed polarity appears between the two granule agglomerations. Increasing the number of granules from seven to thirteen (two rows) leads to an accentuation of the phenomenon (Fig. 13.b).

It can be assessed that the field decreases more if the charge and the number/rows of granules are higher and the initial field is weaker. In extreme conditions the granule agglomerations act as two virtual electrodes where the electric field reverses polarity and can double its intensity. As a consequence, the electrical force that attracts other charged granules to the electrodes could even block the separation process: charged granules will be attracted towards the electrode of the same sign, leading to a decrease in purity and recovery rate.

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