Design and Test of a Novel Fluidized-bed Two-insulated-rolls-type Tribo-aero-Electrostatic Separator for Granular Plastics

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***Abstract* - The quantities of waste plastics that need to be recycled increase every year. Mixed plastics are sorted into polymer type, either by trained operators or by using advanced techniques such as X-ray fluorescence, infrared and near infrared spectroscopy, electrostatic separation and flotation. The selective sorting of the granular plastics mixtures having similar size, density, magnetic and electric properties involves the use of tribo-electrostatic separators.**

This paper introduces a novel tribo-aero-electrostatic separator for granular plastic mixtures, characterized by:

- **a modular fluidized-bed tribocharging device,**
- **two high-voltage electrodes of circular-sector shape to generate the electric field,**
- **two rotating insulated rolls to evacuate the separated granules,**
- **an open separation chamber allowing to evacuate the middling fraction.**

A synthetic mixture of Polyamide (PA) and Polycarbonate (PC) granules was prepared, and the design of experiments methodology was employed for the study of the new tribo-aero-electrostatic separator. The outcome of separation process was modeled as function of three variables: the feed rate of the granular mixture, the level of the high voltage supplying the electrodes and the fluidizing air flow rate. The purity and the recovery of the sorted fractions put in evidence the high efficiency of this new equipment in the processing of granular plastic mixtures.

I. INTRODUCTION

The increased quantities of waste mixed plastics that need to be recycled every year must be first sorted into polymer type, either by trained operators or by using advanced techniques such as X-ray fluorescence, infrared and near infrared spectroscopy, electrostatic separation and flotation.

Triboelectrostatic separation represents a solution for the selective sorting of plastic mixtures, whenever the components have similar size, shape, density, magnetic permeability and electric conductivity. The efficiency of this technique has already been proven [1 - 7]. In a triboelectrostatic separator the plastic granules are charged by tribo-electric effect and separated by the electric field forces. The typical structure of a triboelectrostatic separator contains a tribo-charging device [8-15] where the granules get charged by collisions and frictions with each-others or with the walls of the device. The positively and negatively charged granules are driven in opposite directions by the forces of the electric field generated by two high-voltage electrodes [16-22] and are collected by appropriate means, as separation fractions.

The results of the triboelectrostatic separation are strongly dependent of the efficiency of the tribocharging process. The fluidized- bed devices have proven their efficiency and can be used as charging device in the triboelectrostatic separators [13, 14, 23]. In a "classical" fluidized-bed triboelectrostatic separator the granular mixture is electrified for a time interval of a few minutes in a fluidized–bed tribocharger then separated in the electric field generated by the vertical electrodes of a free-fall electrostatic separator [18-22]. This "two-stage" separation process (charging and separation) is not the most efficient from practical point of view; a continuous one is more convenient. In the tribo-aero-electrostatic separators with continuous operation, tribocharging and separation processes are combined into one operation and take place in the same separation chamber [24-27].

The granules are charged and separated simultaneously but, in order to preserve a continuous operation of the fluidized-bed and to assure an efficient tribocharging process, the feed-rate must be continuously and precisely adjusted, depending on the granular mixture composition, changing in the granules physical characteristics or environmental conditions.
So, the wide-scale application of the triboelectrostatic separation in waste recycling is hampered by the strong dependence of this technique of the amount and homogeneity of the granules charge and its sensibility to the environmental conditions.

The aim of this paper is to present the design and the test of a novel tribo-aero-electrostatic separator (Fig. 1) which objectives are to improve the efficiency of the separation process and to increase the process robustness. In this separator, the granular mixture (A and B) is introduced in the tribocharging chamber (1) where, under the influence of the fluidizing air flow (2), the granules are maintained in a fluidized state and get charged by multiple collisions with each-other and with the insulated rolls (7, 8). A high intensity electric field is generated in the tribocharging chamber zone by two circular-sector type electrodes (3, 4), driving 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}, they rotate with the rolls, exit the electric field zone, detach from the rolls surface under the action of the gravitational force F_g and are collected as separation fractions A and B. Insufficiently charged granules exit the tribocharging chamber at the opposite end with respect to the feeding (Fig.2), enabling a continuous material flow and a continuous operation of the fluidized bed.

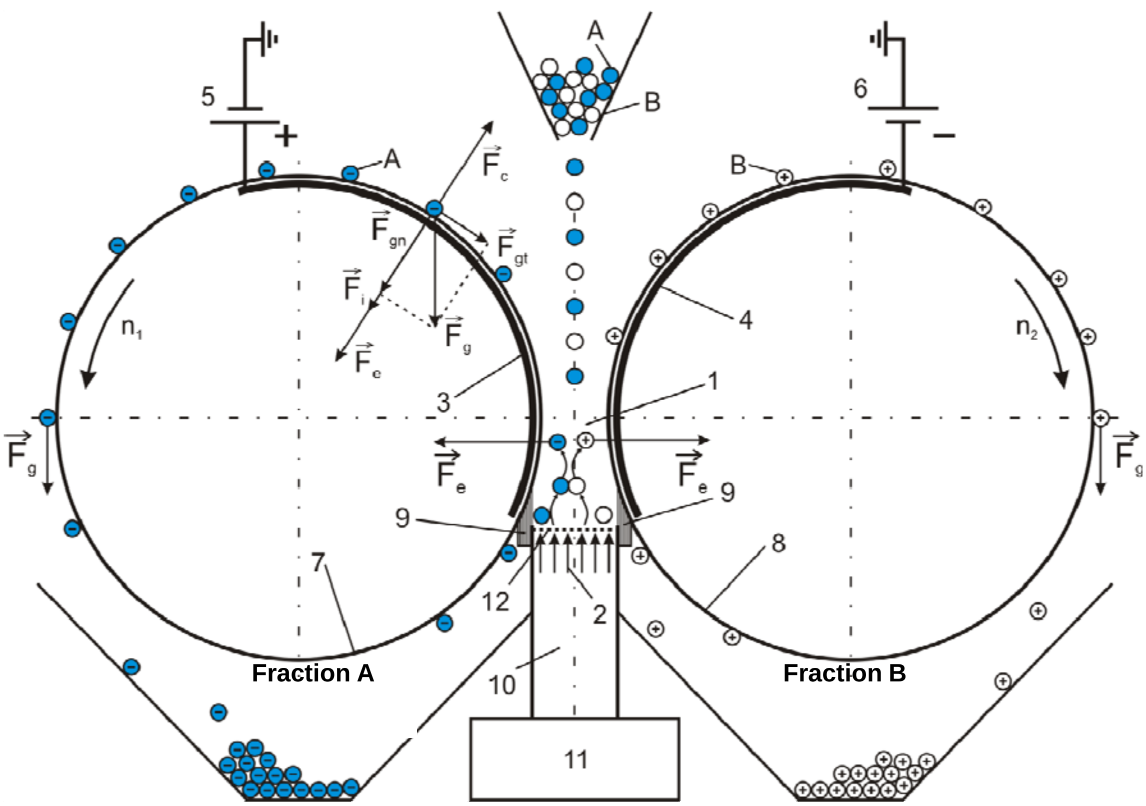


Fig. 1. Components of the novel fluidized-bed two insulated-rolls-type tribo-aero-electrostatic separator 1 – tribocharging room;
2 – fluidizing air; 3 – positive, circular-sector type electrode; 4 – negative, circular-sector type electrode; 5 – HV supply, positive polarity; 6 – HV supply, negative polarity; 7 – rotating insulated roll associated to the positive electrode; 8 – rotating insulated roll associated to the negative electrode; 9 – sealing and wiper brush; 10 – fluidization room; 11 – turbo-blower with air flow control;
12 - filter.

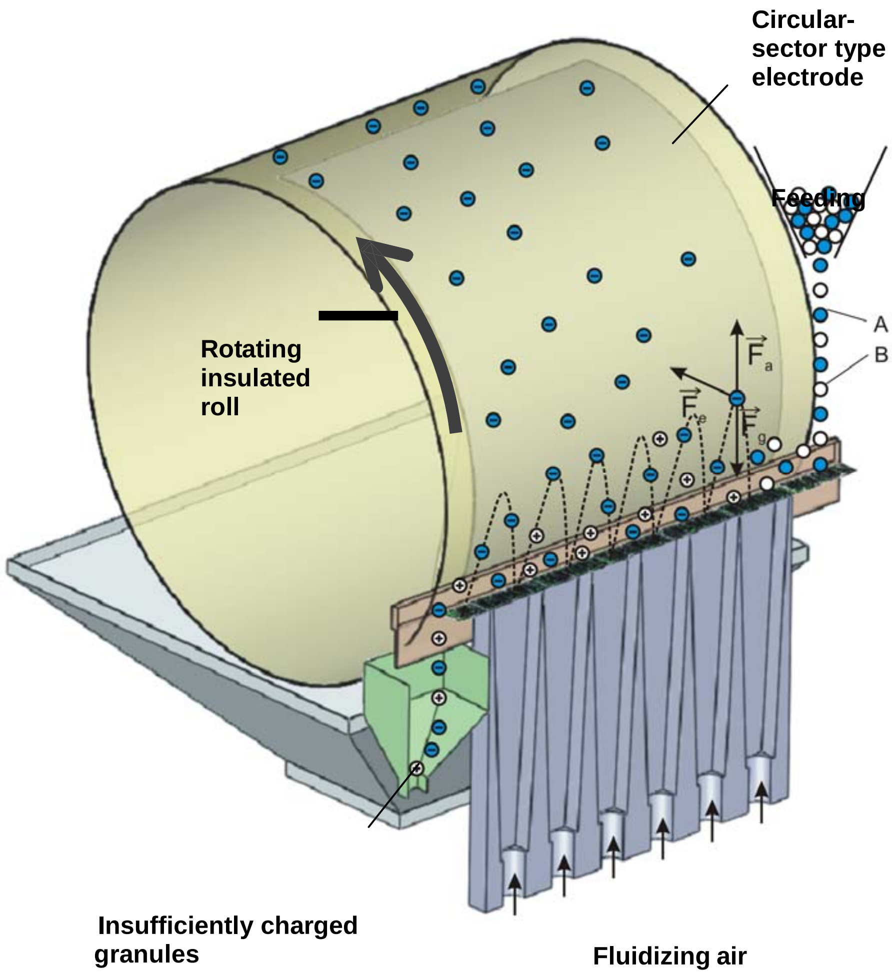
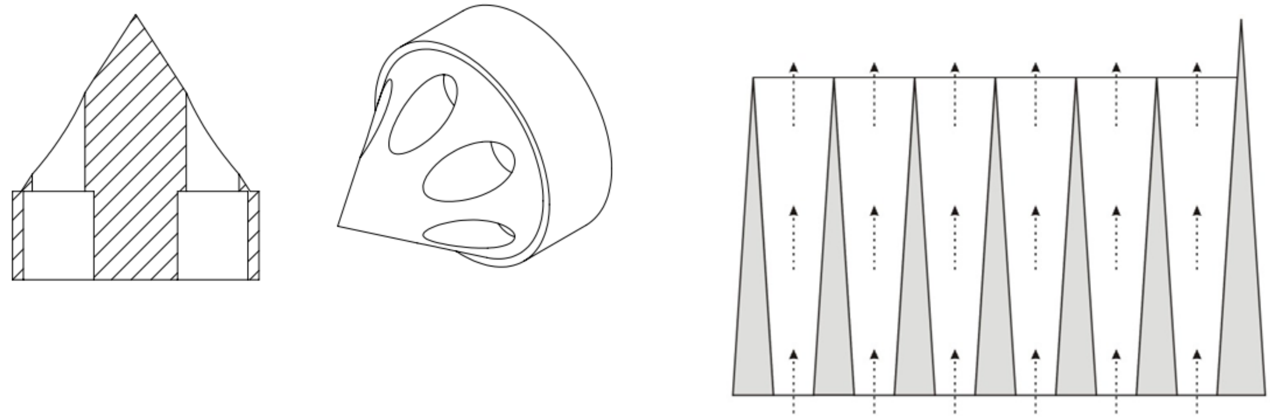


Fig. 2. Charging and separation process in the novel tribo-aero-electrostatic separator.

II. SEPARATOR DESIGN

A. MODULAR DESIGN OF THE FLUIDIZED-BED TRIBOCHARGER

The tribocharging device represents a key element of the triboelectrostatic separation process, with a crucial influence on the process efficiency. In a fluidized-bed tribocharger the granules are maintained in a fluidized state by the ascending air, in order to experience multiple collisions with each-other and with the walls of the device [12]. In order to assure a quasi-uniform distribution of the air flow throughout the cross-section of the tribocharging chamber and optimum conditions for the tribocharging process, the air flow delivered by the turbo-blower was uniformly divided in six streams (Fig. 3a) and the air chamber of the separator was also divided in six compartments (Fig. 3b).



a.

b.

Fig. 3. Divider of the turbo-blower air flow (a) and the six compartments air chamber of the separator (b).

This modular design of the air chamber allows also an adjustable sequential operation of the six air streams, increasing the robustness of the process by adapting the fluidized-bed operation to the characteristics of the granular material.

B. CIRCULAR-SECTOR-TYPE ELECTRODES AND ROTATING INSULATED ROLLS

The electric field generated by the high-voltage electrodes of the separator drives the charged granules in opposite directions, under the action of the electric field force

$$F_e = Q \cdot E \quad (1)$$

where Q is the granule charge and E is the electric field strength.

If the charged granule is in contact with the electrode [24-27], a discharging process occurs and both electric field force F_e and electric image force F_i pinning the granule on the electrode surface diminish, so that, under the action of the air flow force F_a (Fig. 2), the granule could return in the fluidized-bed chamber. The electric image force can be evaluated by the formula:

$$F_i = Q^2/[4\pi\varepsilon_0(2r)^2] \quad (2)$$

where r is the granule radius, considered of spherical shape and ε_0 is the free space permittivity.

The high-voltage electrodes of the novel tribo-aero-electrostatic separator are of circular-sector shape and two insulating rolls rotate around (Fig. 2), so that the charged granules are not in contact with the metallic electrodes. The electric field generated by the two high voltage electrodes (Fig.4) drives the charged granules in opposite direction and pin them on the surface of the rotating insulated rolls.

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 [Fig. 5]. In consequence, the pinning force

$$F_n = F_e + F_i + F_{gn} \quad (3)$$

is almost constant.

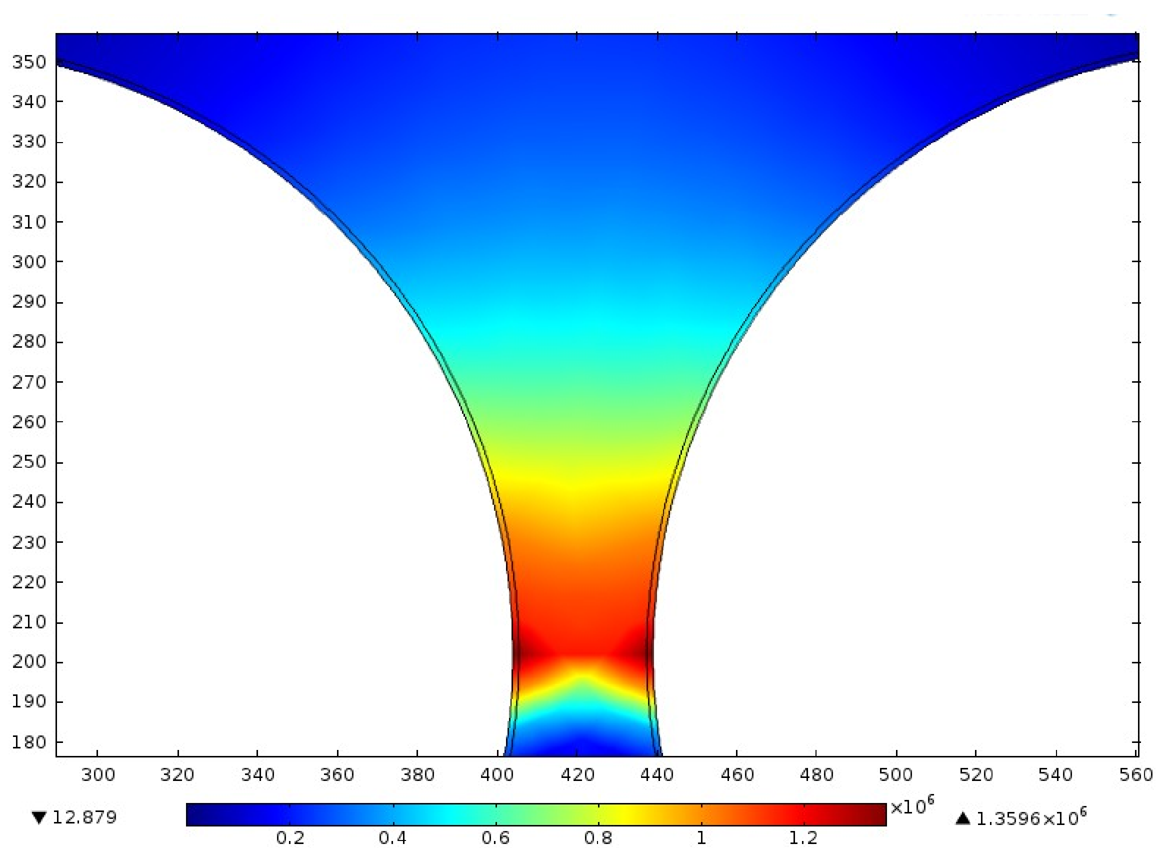


Fig. 4. Electric field distribution between the high voltage electrodes of the novel tribo-aero-electrostatic separator, supplied at ±20 kV.

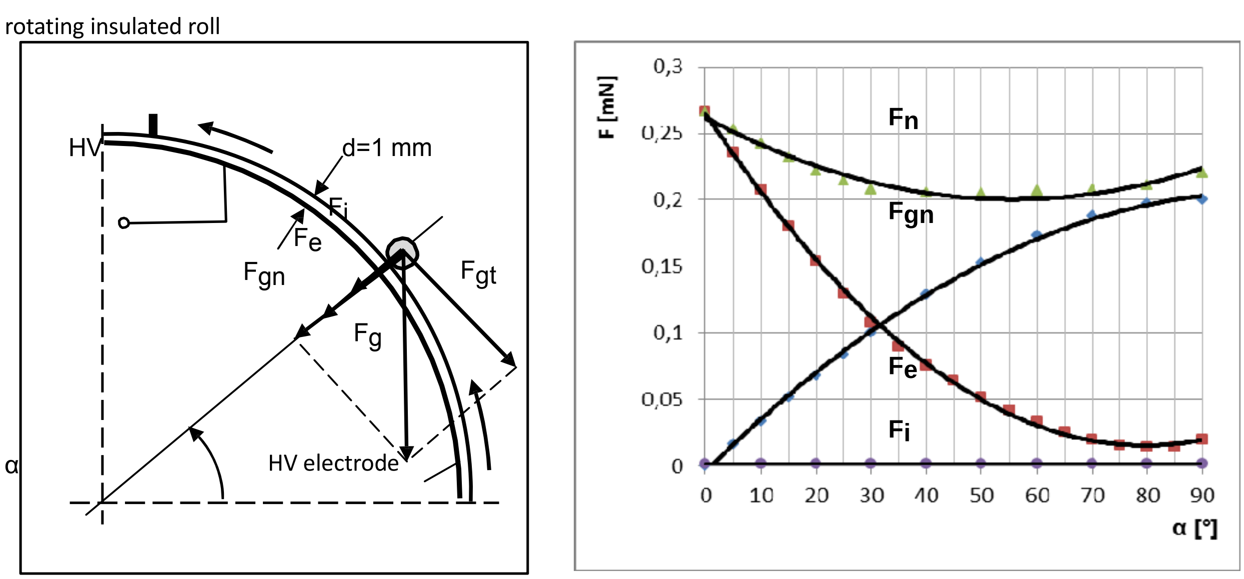


Fig. 5. Forces acting on a charged granule pinned on the surface of the insulated roll (a) and evolution of the pinning forces versus granule position α (b). The granule mass was considered 20 mg and the charge 0.2 nC. The electric field strength was calculated for ± 20 kV high voltage level.

The cylindrical-sector shape of the high-voltage electrodes and the two rotating insulated rolls improve the pinning effect of the charged granules and avoid their return in the fluidized bed.

III. EXPERIMENTAL MODELING OF THE SEPARATION PROCESS

The granular mixture is introduced in the tribocharging chamber where the granules get charged by colliding against each other and with the insulating rolls. The electric field generated by the two circular-sector type electrodes drives in opposite directions the positive and the negative charged granules. Pinned on the rotating insulated rolls under the action of the force F_n given by (3) the charged granules are removed from the tribocharging chamber and collected as separation fractions (Fig. 1). Insufficiently charged granules exit the tribocharging chamber at the opposite end with respect to the feeding and are then added to the feeding material.

A. MATERIAL AND METHOD

A balanced granular mixture of polyamide (PA) and polycarbonate (PC) was prepared (Fig. 6) and the Design of Experiments methodology was used in order to test the efficiency of the novel tribo-aero-electrostatic separator. The material flow-rate, the fluidization air flow-rate and the potential difference between the high-voltage electrodes have been chosen as input factors while the mass and the purity of the sorted fractions as well as the separation efficiency were considered to be the responses of the process. The separation efficiency was defined as ratio of the mass of the material collected as sorted fractions and the material introduced in the process:

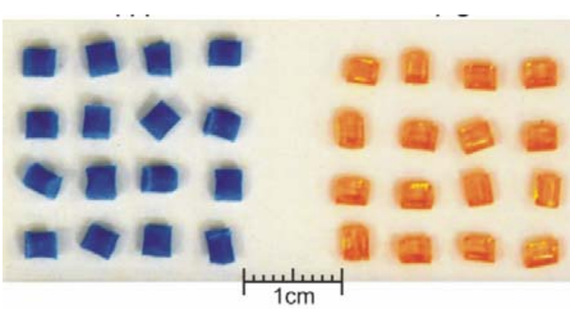
$$\eta = (m_{PA} + m_{PC}) / (D_m \cdot \Delta t) \tag{4}$$

m_{PA} – mass of the material collected in the PA compartment of the collector [g]
m_{PC} – mass of the material collected in the PC compartment of the collector [g]

D_m - material flow-rate [g/s]

Δt - duration of the separation process [s]

Based on preliminary experiments, the material flow-rate was modified between 3.5 and 7.5 g/s, the fluidization air flow-rate between 100 and 130 m^3/h (corresponding to 35…45 Hz - frequency of the converter supplying the turbo-blower motor) and the potential difference of the high-voltage electrodes between 40 and 52 kV.



Material	Polyamide PA	Polycarbonate PC
Color	blue	orange
Shape	cylindrical	cylindrical
Dimension [mm]	Φ 2.5 X 3.4	Φ 3 X 3.6
Mass [mg]	20	25
Density [kg/m^3]	1100	1200

Fig. 6. Aspect (a) and characteristics (b) of PA and PC granules used in tribo-aero-electrostatic separation.

B. RESULTS AND DISCUSSIONS

According to the Design of Experiments methodology, 17 separation experiments (3 experiments in the central point) were carried out (Fig. 7) and the results are presented in the Table 1. Based on the experimental results, MODDE 5.0 program [28] calculated the polynomial mathematical model for the output variables (process responses):

$$m_{PA} = 109.54 + 4.31D_m + 2.9U + 1.95f + 5.42D_m^2 + 2.31U^2 + 0.47f^2 + 1.78D_{mU} - 1.56D_mf - 0.77Uf$$
$$m_{PC} = 116.64 + 33.48D_m + 6.55U + 0.46f + 0.68D_m^2 + 0.2U^2 - 2.3f^2 + 1.02D_mU - 0.68D_mf - 0.29Uf$$
$$p_{PA} = 97.9 - 0.91U + 0.01f + 0.11D_m^2 + 0.03U^2 + 0.36f^2 + 0.08D_mU + 0.05D_mf + 0.18Uf$$
$$p_{PC} = 97.83 - 0.12D_m - 1.41U + 0.04f + 0.09D_m^2 - 0.16U^2 + 0.02f^2 + 0.03D_mU + 0.01D_mf - 0.07Uf$$
$$\eta = 67.09 + 2.35D_m + 2.31U + 0.51f + 1.35D_m^2 + 0.71U^2 - 0.4f^2 + 0.61D_mU - 0.54D_mf - 0.91\mathrm{Uf}$$

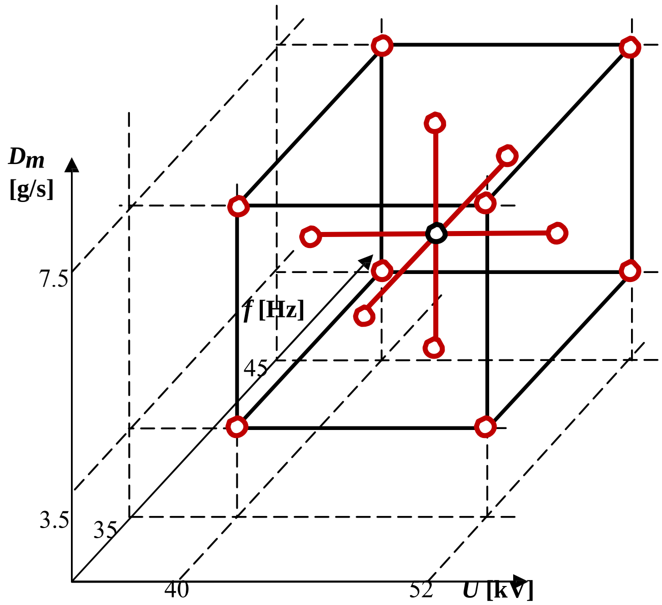


Fig. 7. Experimental points for a 3 factors composite plan

Table 1. Results of the separation experiments of PA/PC mixture in accordance with the experimental plan presented in figure 7.

N0.	D_m [g/s]	U [kV]	f [Hz]	PA mass m_{PA} [g]	PC mass m_{PC} [g]	PA purity p_{PA} [%]	PC purity p_{PC} [%]	Efficiency η [%]
1	3.5	40	35	63.49	65.02	99.84	99.89	60.36
2	7.5	40	35	162.41	144.52	99.36	99.03	65.56
3	3.5	52	35	69.27	75.23	96.24	96.03	68.02
4	7.5	52	35	183.44	164.76	97.05	95.98	77.09
5	3.5	40	45	67.03	68.4	98.86	99.78	66.77
6	7.5	40	45	171.1	142.28	99.99	99.73	68.28
7	3.5	52	45	78.14	82.01	98.2	96.04	70.79
8	7.5	52	45	176	164.29	97.33	95.53	75.65
9	3.5	46	40	72.16	72.93	98.73	98.12	67.56
10	7.5	46	40	183.71	170.71	98.17	98.04	78.64
11	5.5	40	40	118.99	116.37	98.76	98.91	70.82
12	5.5	52	40	113.88	131.77	96.66	96.02	69.59
13	5.5	46	35	108.59	115.23	99.36	97.96	69.06
14	5.5	46	45	118.06	113.6	98.73	97.97	67.26
15	5.5	46	40	100.54	105.87	95.65	96.19	61.6
16	5.5	46	40	106.05	123.41	96.83	99.19	69.4
17	5.5	46	40	100.5	103.81	99.1	97.97	60.77

Some of predicted equal PC mass contour are plotted in the figure 7, showing that, the potential difference between the high-voltage electrodes in the range (40…52) kV has not a great influence on the quantity of the separated material. The same conclusion is valid for the frequency interval (35…45) Hz. According to this figure, the input factor having the greater influence on the PC mass is the material flow-rate D_m. An analysis of the PC fractions purity (Fig. 8) leads to the conclusion that, from this point of view, the most important input factor is the potential difference U between the high voltage electrodes. Similar results have been obtained for PA fraction.

As the figure 9 presents, the process efficiency is more influenced by the high voltage level and by the material flow-rate, and less influenced by the fluidization air flow-rate.

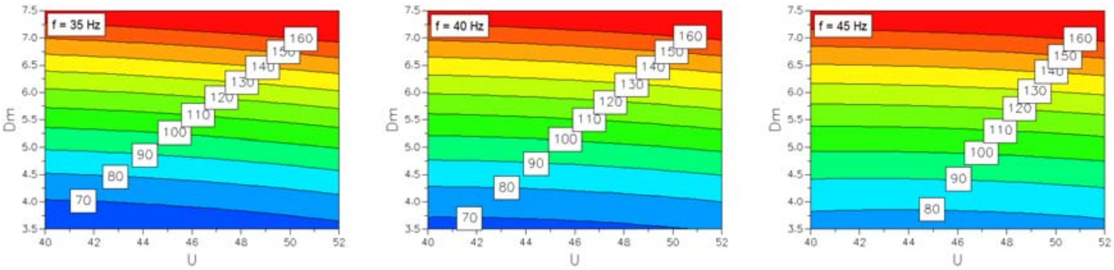


Fig. 7. Equal mass contour plots of PC fraction, predicted by MODDE 5.0, based on the experimental results presented in the Table 1.

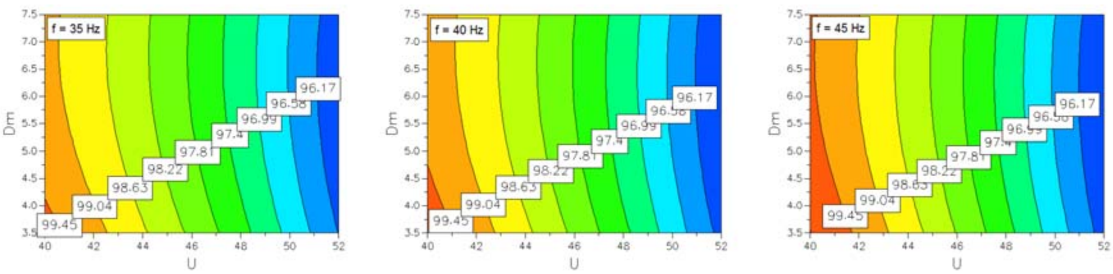


Fig. 8. Equal purity contour plots of PC fraction, predicted by MODDE 5.0, based on the experimental results presented in the Table 1.

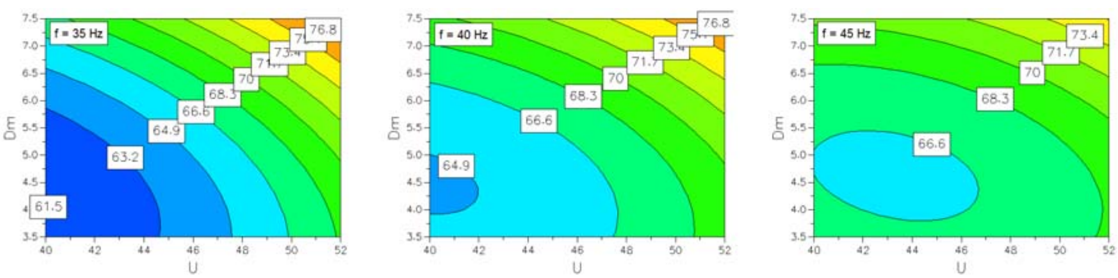


Fig. 9. Separation efficiency contour plots predicted by MODDE 5.0, based on the experimental results presented in the Table 1.

IV. CONCLUSIONS

The novel tribo-aero-electrostatic separator presented in this paper distinguishes itself from other separators by the followings features:

- a modular design of the air chamber, assuring a quasi-uniform and adjustable fluidizing air flow for the tribocharging process;
- the tribocharging chamber is open at the end opposite to the feeding, so that insufficiently charged granules exit the separation process, assuring a continuous material flow and a continuous operation of the fluidized bed for a wide range of the feeding rate and of the granular mixture composition;
- a common tribocharging chamber and electric field zone, driving the positively-and negatively-charged granules in opposite directions, under the action of the electric field forces;
- circular-sector shape of the high-voltage electrodes and rotating insulated rolls, in order to pin the charged granules on the rolls surface, avoiding the discharging process. So, the pinning force is almost constant and the charged granules are removed from the tribocharging chamber being collected as separation fractions.

The experimental results put in evidence the high efficiency and the robustness of the new tribo-aero-electrostatic separator. A continuous operation allows to separate up to 80% of the feeding material and the best results have been obtained for a balanced granular mixture composition.

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