Two Stage Electrostatic Separator for the Recycling of Plastics from Waste Electrical and Electronic Equipment

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***Abstract* -- The aim of study was to evaluate the effectiveness of a new facility for the recycling of plastics from granular waste electrical and electronic equipment. The installation consists of two sections, the products of a first tribo-aero-electrostatic separator being subsequently treated in two free-fall electrostatic separators. The tests were performed on a mixture of polycarbonate (PC) and polyamide (PA). Analysis of the purity of the products obtained was performed using a new program of image processing in MATLAB. Products of very high purity (over 95% for the PC and almost 100% for PA) were obtained at a recovery rate higher than 70%.**

***Index Terms*-- electrostatic processes, image processing, triboelectricity, recycling, waste recovery**

I. INTRODUCTION

Computers, printers, mobile phones, and other such appliances have shorter and shorter lifetimes [1], due to the very fast progress in electronics and information technology (IT). They represent an increasingly larger part of the waste electrical and electronic equipments (WEEE), the volume of which has reach an alarming level, especially during the last twenty years, when the markets have been saturated with huge quantities of new products of this type [2], [3]. According to the recent statistics, the quantity of WEEE increased by 25% in five years, with the proportion of plastics amplified by 30% in the same period [1], [4 - 6]. This situation has drawn the attention of both governmental and non-governmental organizations on the necessity of developing effective methods for the recycling of WEEE.

The electrostatic separation methods [7 - 9] have already proved to be a very effective solution for the recycling of insulating materials contained in this kind of waste. This non-pollutant technology is characterized by weak energy consummation, as well as by reduced costs of operation and maintenance [10].

The triboelectricity, a physical phenomenon involving the charge transfer between two bodies in contact [11 - 16] is the main charging mechanism employed for the separation of granular insulating materials in an intense electric field. The aim of the present work is to validate a new tribo-electrostatic separation process that has been designed for increasing the purity of the plastics recovered from WEEE.

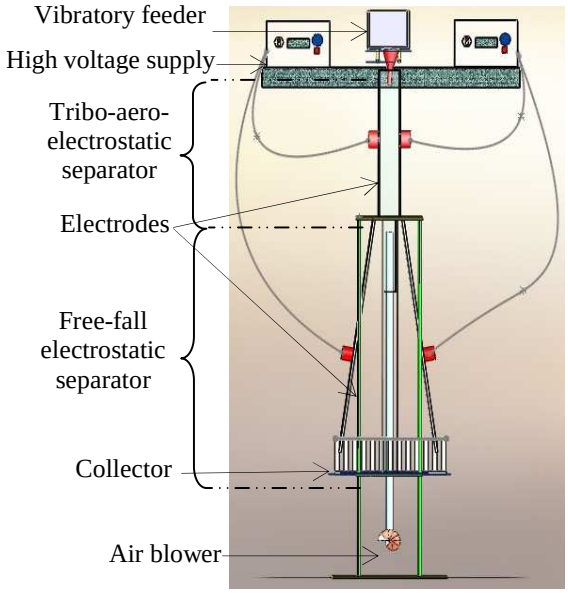

Fig. 1. Schematic representation of the new double-stage electrostatic separator for mixed granular plastics.

II. EXPERIMENTAL SET-UP

The installation is composed of two superposed, detachable electrostatic separators, attached to a same vertical support (Fig. 1). The upper section of the set-up is a tribo-aero-electrostatic separator that consists in a parallelepiped enclosure (height: 500 mm; width: 130 mm; depth: 110 mm), having two transparent walls in order to permit the visualization of phenomena, and two opaque lateral walls that have aluminum plate electrodes glued on their internal surfaces. These electrodes are energized from two adjustable DC high voltage supplies of opposite polarities ± 50 kV, to create an electrical field sufficiently strong to control the trajectories of charged granules.

Granule charging is produced by tribo-electric effect in the fluidized bed generated in the interior of this enclosure (Fig.1). The fluidization air is furnished by a variable –speed blower. The uniformity of the fluidization bed is ensured by a custom-designed air diffuser, which is a finely-perforated plate situated at the bottom of the upper section of the installation.

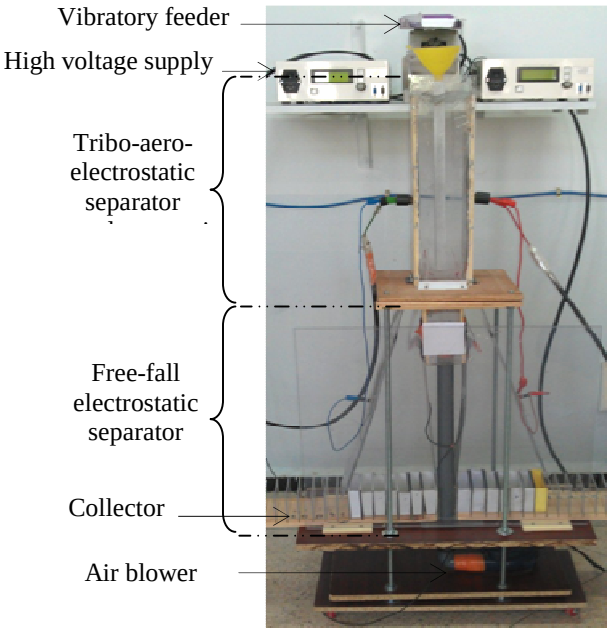

Fig. 2. Photograph of the experimental set-up.

The granules are introduced in the separation enclosure by a funnel supplied by a fully-adjustable vibratory feeder. Under the combined action of the gravitational, aerodynamic, and electrical forces, they separate essentially in function of the polarity of their charge and exit the first separation stage through two slots that direct them to the lower section of the experimental set-up (Fig. 2). This section is composed of two free-fall electrostatic separators, the electrodes of which are aluminum plates (520 mm x 100 mm) glued to four insulating PMMA boards (650 mm x 110 mm).

The upper edges of these four boards are positioned at the exit of the tribo-aero-electrostatic separator. The two vertical central plaques are fixed and connected to the earth, while the two exterior electrodes are connected to high voltage supplies of opposite polarities and can rotate to form angles ranging from 0° to 45° with respect to the vertical. The separated products are recovered in two identical collectors, each subdivided in twenty compartments (length: 100 mm; width: 30 mm; depth: 85 mm).

III. Materials and Method

The experiments have been carried out with granules of polycarbonate (PC) and polyamide (PA) (Table 1) used in the plastics industry. The separation of these granules by mechanical proceedings is impossible, because they have similar shapes and mass densities. The analysis of the purity of the separated products is facilitated by the fact that the granules have different colors. In order to measure the mass of a granule, a set of 100 granules were weighted and the results was divided by 100.

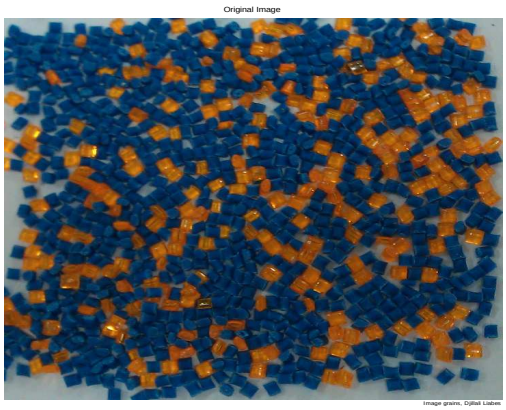

Fig. 3. Aspect of the PC – PA granular material.

TABLE 1: Characteristics of the Granules of Plastics Employed in the Experiments

Granule	PA	PC
Colour	Blue	Orange
Form	Cylindrical	Cylindrical
Size [mm]	Ø 2.5 x 3.4	Ø 3 x 3.6
Mass [mg]	20	25
Density [kg/m3]	≈1100	≈1200

The high-voltage U_1 applied to the electrodes of the upper section was adjusted at various values ranging between 24 and 48 kV. The electrodes of the two free-fall electrostatic separators of the lower section were energized at voltages U_2 and U_3 of opposite polarities and similar absolute values in the range 24 to 32 kV.

The other variables of systems were maintained constant: the speed of the air blower: 13000 rev/min; the relative humidity of the air $RH = 41 \pm 1\%$; the room temperature $T = 18 \pm 1°C$; the mass and composition of the granular product samples m = 100 g (PC) + 100 g (PA) = 200 g ; the feed-rate: D = 1 g/s. The movable electrodes of the inferior floor have been inclined at $\alpha = 32°$, their inferior edges correspond to the seventh compartment of each collector.

The mass of the granules recovered in each one of the seven first compartments of the two collectors was measured by using an electronic scale (resolution: 0.01g). The purity of the products has been evaluated using an image processing program for analyzing the photos of the granular materials collected in one or several compartments (Fig. 3). This program uses the so-called « the k-means » algorithm and calculates the number of pixels correspondent to each color, so that to determine the ratio between the number of PC and PA granules. In the example illustrated by figures 4 and 5, that correspond to the product obtained in the compartments 3 to 7 of the collector PA in the sixth experience of table 2, the composition given by this method is: 76% PA and 24% PC.

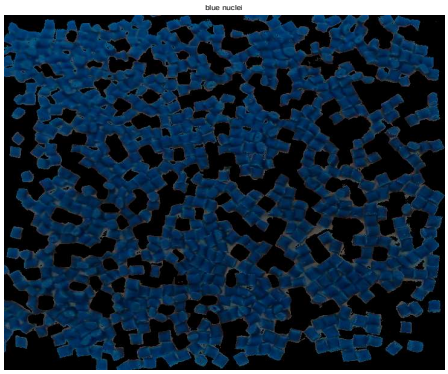

Fig. 4. Processed image of a PC-PA granular mixture. showing only the PA granules.

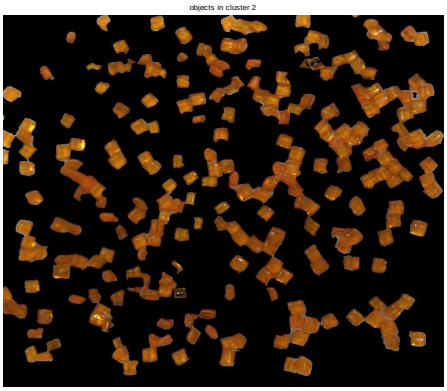

Fig. 5. Processed image of a PC-PA granular mixture. showing only the PC granules.

The experimental modeling of the separation process has been performed using the response surface methodology [17, 18], which recommends the use of a composite factorial experimental design and the adoption of a quadratic model. For the factors considered hereafter, namely the high-voltages U_1, U_2 and U_3 applied respectively to the upper section electrodes, and to the two pairs of electrodes in the lower section of the experimental setup, the model y of the response (i.e. the mass m and in some cases the purity p of the material collected in the third to the seven compartment), will take the following form:

$$y = a_0 + a_1 U_1 + a_2 U_2 + a_3 U_3 + a_{12} U_1 U_2 + a_{13} U_1 U_3 + a_{23} U_2 U_3 + a_{11} U_1^2 + a_{22} U_2^2 + a_{33} U_3^2 \quad (1)$$

The experimental data were analyzed with MODDE 5.0 software (Umetrics, Sweden) [19], which calculates the coefficients of the mathematical model, draws the response contours and identifies the best adjustments of the parameters for optimizing the process. Moreover, the program calculates two statistical criteria: the goodness of fit: R^2, and the goodness of prediction: Q^2. The latter is a measure of how well the model will predict the responses for new experimental conditions. In the case of a good mathematical the criteria R^2 and Q^2 have numerical values close to the unit.

TABLE 2: MASS OF PC GRANULES COLLECTED IN BOXES #1 TO 7, (COMPOSITE FACTORIAL EXPERIMENTAL DESIGN)

U_1 [kV]	U_2 [kV]	U_3 [kV]	Box # 1	2	3	4	5	6	7
24	24	-32	8.19	10.2	19.4	15.8	22.4	15.6	12.6
48	24	-32	6.17	9.54	16.7	12.4	21.4	19.6	13,0
24	32	-32	8.66	7.8	12.3	12,0	20.3	16.9	20.2
48	32	-32	9.53	8.63	14.6	11.5	18.7	18.6	15.7
24	24	-24	5.92	7.4	12.3	13.9	20.3	19.3	20.2
48	24	-24	7.18	7.89	12.9	11.5	18.2	20.1	20.1
24	32	-24	7.46	9.17	13.3	13.5	18.6	16.6	21.2
48	32	-24	11.2	12.5	16.5	13.2	17.6	16.6	10.5
24	28	-28	6.39	6.85	10.3	12.3	18.7	18.7	25.6
48	28	-28	7.35	9.62	13.6	15.0	18.2	15.0	18.4
36	24	-28	5.51	8.42	14.8	14.3	20.5	18.2	16.5
36	32	-28	9.09	7.34	10.1	10.5	23.9	17.7	20,0
36	28	-32	8.93	10.0	13.3	12.5	17.6	16.8	19.1
36	28	-24	9.07	10.8	14.5	14.4	19.0	15.2	16,0
36	28	-28	6.61	9.48	14.5	15.1	18.7	17.4	14.8
36	28	-28	11.1	11.6	16.9	15.6	17.7	13.1	11.8
36	28	-28	8.03	9.12	13.9	15.4	16.9	14.8	17.1

TABLE 3: MASS OF PA GRANULES COLLECTED IN BOXES #1 TO 7, (COMPOSITE FACTORIAL EXPERIMENTAL DESIGN)

U_1 [kV]	U_2 [kV]	U_3 [kV]	Box # 1	2	3	4	5	6	7
24	24	-32	20.4	13.8	14.2	8.96	15.9	14.7	7.77
48	24	-32	4.11	6.8	8.03	7.38	17.2	22.6	31.7
24	32	-32	14.1	18.9	15.4	10.1	18.0	13.4	9.23
48	32	-32	5.01	5.9	9.51	9.65	19.3	24.1	25.7
24	24	-24	23.7	14.4	12.5	11.2	17.0	16.1	6.91
48	24	-24	5.34	5.61	8.74	9.96	24.7	27.4	18,0
24	32	-24	13.8	15.1	14.2	9.48	19.9	15.5	7.33
48	32	-24	3.8	7.07	7.83	8.54	21.1	24.6	23.7
24	28	-28	12.4	12.5	15.4	10.1	20.9	18.8	10.9
48	28	-28	11.1	11.9	10.7	11.2	24.4	10.2	10.0
36	24	-28	11.4	14.2	13.8	12.0	24.2	15.2	10.5
36	32	-28	12.1	13.5	12.8	10.1	20.8	18.6	14.9
36	28	-32	10.4	11.3	11.5	7.61	20.0	20.8	15.5
36	28	-24	14.1	14.0	12.7	9.66	16.8	15.2	16.7
36	28	-28	9.08	15.7	12.6	9.03	17.4	15.8	17.5
36	28	-28	16.3	13.7	12.3	9.16	18.0	14.0	15.4
36	28	-28	20.4	13.8	14.2	8.96	15.9	14.5	7.77

IV. RESULTS AND DISCUSSION

The results of the seventeen experiments carried out according to the composite factorial design are reported in tables 2 and 3. For each experiment, the overall purity of the granular materials collected in boxes #3 to 7 was analysed with the image processing program previously-described and the results are given in table 4. The mathematical models of the responses P_{PC} (goodness of fit R^2 =98.3%, goodness of prediction Q^2 = 92.6%), P_{PA} (R^2= 97.1%, Q^2=88.0%), R_{PC} (R^2 =98.6%, Q^2 = 84.7%) and R_{PA} (R^2 =99.5%, Q^2 =95.4%), computed with MODDE 5.0, were:

TABLE 4: MASS OF PA GRANULES COLLECTED IN BOXES #1 TO 7, (COMPOSITE FACTORIAL EXPERIMENTAL DESIGN)

U_1 [kV]	U_2 [kV]	U_3 [kV]	Purity P_{PA}[%]	Recovery R_{PA}[%]	Purity P_{PC}[%]	Recovery R_{PC}[%]
24	24	-32	58.33	94.41	62.72	82.39
48	24	-32	81.47	85.55	83.29	84.11
24	32	-32	81.34	93.05	89.14	83.23
48	32	-32	83.73	80.94	89.24	81.35
24	24	-24	85.3	94.05	80.95	86.6
48	24	-24	76.21	85.81	90.71	84.63
24	32	-24	92.22	94.38	85.1	83.37
48	32	-24	59.97	84.13	73.95	75.88
24	28	-28	83.81	92.69	86.36	86.63
48	28	-28	78.94	83.64	90.17	85.57
36	24	-28	79.49	86.74	74.02	86.85
36	32	-28	84.63	85.95	76.16	83.36
36	28	-32	89.01	86.83	93.24	80.72
36	28	-24	91.04	88.38	95.16	79.89
36	28	-28	94.42	85.86	90.65	84.36
36	28	-28	93.73	85.81	90.25	84.82
36	28	-28	94.13	86.19	92.45	85.02

$$P_{PC} = 89.63 + 2.3U_1 + 2.19U_2 - 5.17U_1*U_2 - 2.75U_1*U_3 - 5.62U_2*U_3 - 13.43U_2^2 + 5.67U_3^2 \quad (2)$$

$$P_{PA} = 91.37 - 2.1U_1 + 2.1U_2 + 5.48U_1*U_2 - 8.35U_1*U_3 - 4.32U_2*U_3 - 7.96U_1^2 - 7.28U_2^2 + 0.68U_3^2 \quad (3)$$

$$R_{PC} = 84.58 - 1.06U_1 - 1.74U_2 - 1.14U_1*U_2 - 1.16U_1*U_3 - 1.25U_2*U_3 + 1.62U_1^2 - 4.17U_3^2 \quad (4)$$

$$R_{PA} = 86.21 - 4.85U_1 - 0.81U_2 + 0.59U_3 - 0.65U_1*U_2 + 0.57U_2*U_3 + 1.75U_1^2 + 1.19U_3^2 \quad (5)$$

According to these models, the purity of the separated materials may be as high as 96% for PC and 93 % for PA (Figs. 6 and 7). The maximal value for the purity of PC is obtained at high U_1 and moderate U_2. At higher U_2, the purity of the recovered product would be reduced as a consequence of the fact that the positively-charged PA granules are deviated by the stronger impacts with the electrode of opposite polarity in the lower section of the installation In the case of PA the best results are obtained at low U_1 and high U_3. The increase of U_1 would intensify the impacts between the negatively-charged PC granules and the electrode of positive polarity in the upper section of the installation.

The lower purities for PA can be explained by the fact that the size and mass of each PC granule is smaller that of a PA granule and thus easier for the airflow to move them in the collecting zone of PA granules. In spite of the increased voltage applied to the electrodes, gravity and aerodynamic forces are stronger that the electrical ones and the granules do not have sufficient time to move out of that zone. They are collected and counted as impurity even if charged with the opposite polarity that the rest of the granules.

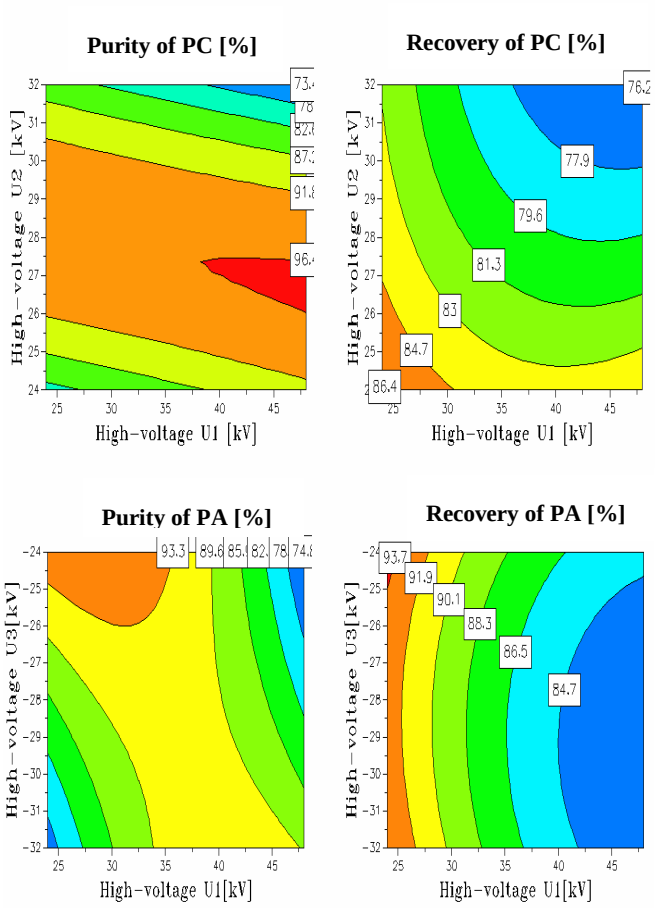

Fig. 6. MODDE 5.0 predicted equal purity [%] and equal recovery [%] contours for PC and PA products].

The best recovery results 86.4% for PC and as high as 93.7% for PA are obtained at the lower values of U_1, for reasons similar to those exposed for the purity. The voltages U_2 and U_3 applied to the electrodes in the lower section of the installation have lesser impact on the recovery of the two products. The predictions in Figs. 6 and 7 can be used for adjusting the values of the applied voltages such as to obtain the optimum performances in terms of purity and recovery.

For instance, according to software MODDE 5.0, the higher purity and recovery of PC and PA are respectively: P_{PC}= 94.96%, P_{PA}= 94.57%, R_{PC}= 84.78% and R_{PA}= 94.9%, which correspond to the following optimal values of the voltages applied to the electrodes: U_1= 24 kV, U_2=27.96 kV and U_3= - 24.36 kV. An experiment performed with these values of the high-voltages conducted to the following results: P_{PC}= 95.57%, P_{PA}= 94.88%, R_{PC}= 86.53% and R_{PA}= 94.3 %, which are very close to the prediction made by MODDE 5.0.

V. CONCLUSIONS

The experiments described in this paper prove the effectiveness of a novel electrostatic separation process for the mixed granular plastics:

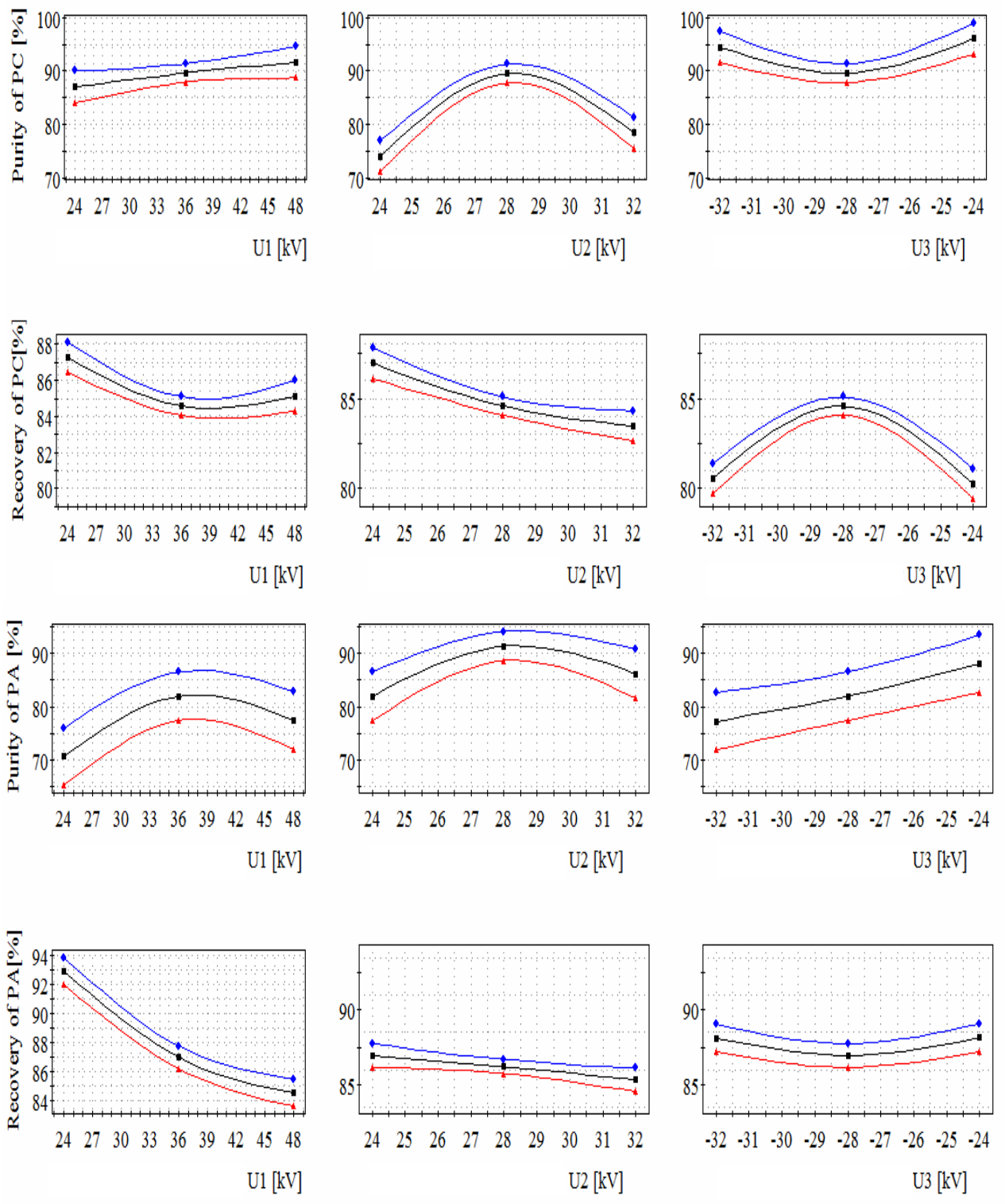

Fig. 7. MODDE-predicted purity and recovery of PC and PA as function of the three applied voltages.
The upper and lower curve on each graph indicate the limits of the 95% confidence level interval

1) In other to ameliorate the purity and recovery of plastic materials recuperated from waste electrical and electronic equipments, the products of the first tribo-aero-electrostatic separation can be submitted to a second sorting, in the electrical field of two free-fall electrostatic separators. The tribo-aero-electrostatic separator and the two electrostatic separators of freefall represent respectively the upper and lower sections of the same installation.
2) The techniques of image processing and analysis facilitate the determination of the purity and recovery of the separated products.
3) The experimental design methodology enables the modeling and the optimization of the installation.

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