Numerical Study of a Semi-Industrial Electrostatic Separator of Ternary Plastic Granular Mixture

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Abstract **-** Recycling is the subject of the most analyzed studies today. This is a problem on which manufacturers are working more and to which the general public is increasingly sensitive. The objective of the present work is to simulate the intermittent operation of a semi-industrial tribo-aero-electrostatic separation process for a mixture of three granular materials by the development of a simple mathematical model, of which it has been assumed that the probability of A separation of the granules can be presented using the normal distribution law, depending on the number of impacts with granules belonging to other classes of materials and to justify the presence of impurities in the collector tanks.

Keywords **-** Semi-industrial electrostatic separator, ternary granular mixing, numerical simulation, Triboelectricity.

I. INTRODUCTION

Production of electrical and electronic equipment is one of the fastest growing manufacturing activities.

This leads to increased quantities of waste electrical and electronic equipment (WEEE) that need to be recycled [1, 2]. Fig 1. Schematic side-view of the "standard" configuration of the tribo-aero-electrostatic separator for granular mixtures of insulating materials.

The evolution of environmental standards has made eco-design a priority, promoting the dismantling and reuse of obsolete products [3] – [4]. The use of good quality recycled materials has become part of our daily lives, thanks to technological developments [5-6].

A new tribo-aero-electrostatic separator (Fig. 1), which is the object of a patent [7], was put into operation by APR2 Company in France, in January 2014. The separator consists of two air chambers: one for air injection (150 mm x 350 mm x 500 mm) and the other for fluidizing the granular materials and separating them. Two of the walls of the latter chamber are made of Plexiglas. The other two walls are the stainless steel belts (0.2 mm thick, 40 cm wide) of two conveyors, which are also the high voltage electrodes of the separator [8, 9].

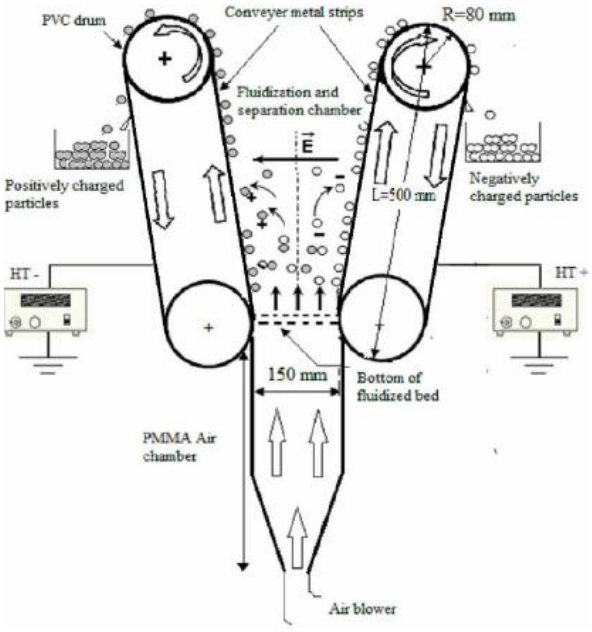


Fig.1. Schematic side-view of the "standard" configuration of the tribo-aero-electrostatic separator for granular mixtures

II. MATHEMATICAL MODEL

The study focuses on the separation of a mixture of three granular materials noted A, B and C. The three classes of granules have similar sizes and masses, however their triboelectric characteristics are different. The particles do not attain saturation, as they

do not spend too much time in the fluidized bed. They are attracted to the electrodes and collected at very low charge levels. The gravitational forces being "balanced" by the aerodynamic forces, the particles move mainly under the action of the electric forces, which will drive them to the electrodes as soon as they got an electric charge [10]- [11].

The mathematical model is based on the assumption that the probability of a granule to be separated can be expressed as a function of the number of impacts it has with the other granules. The number of collisions between individual granules depends on the concentration of each class of materials in the granular mixture. The total mass M(t) of the materials located in the fluidized bed at time t is expressed as follows[12,13]:

$$M(t) = M_A(t) + M_B(t) + M_C(t) \quad (1)$$

The respective concentrations of materials A, B and C are:

$$c_A(t) = M_A(t)/M(t)$$
$$c_B(t) = M_B(t)/M(t) \quad (2)$$
$$c_C(t) = M_C(t)/M(t)$$

In a fluidized bed of known geometry and a controllable air flow, each granule undergoes N (t) collisions per time unit. At t =0, N(0)= N1. It is assumed that the regime of the fluidized bed is not significantly modified by the changes in the mass M(t), which means that N(t) is constant in time, i.e. N(t) = N1. This assumption is based on the fact that in a fluidized bed, at any time, a particle is surrounded by practically the same number of other particles and hence is subjected to the same number of « turbocharging » collisions.

In the case of a mixture in which the three types of particles have the concentrations $c_A(t)$, c_B (t) and c_C (t), each particle c under goes $c_A(t)N$ contacts with type A particles and $c_B(t)N$ contacts with type B particles [19].

Assuming that the material C is between A and B in the triboelectric series, two coefficients λ_{CA}, $\lambda_{CB} < 1$ will be used to characterize the effect of C-A and C-B collisions, respectively. For instance, if a unit a dimensional charge were exchanged at each A-B collision, the non-dimensional charge transferred at a contact between C and A would be λ_{CA}. The coefficients λ_{AC}, $\lambda_{BC} < 1$ define in a similar way the effect of the A-C and B-C collisions. It should be noted that $\lambda_{CA} = \lambda_{AC}$, $\lambda_{CB} = \lambda_{BC}$ and $\lambda_{CA} + \lambda_{CB} = 1$. The values of the coefficient λ depend of the position of the three materials in the tribo-electric series [20]. Thus, the charge acquired by a granule A during a time period t, is due to the number of equivalent collisions XA with B and C:

$$X_A(t) = \int_0^t [c_B(t) + \boldsymbol{\lambda}_{AC} c_C(t)]\, N(t)\, dt \quad (3)$$

$$X_B(t) = \int_0^t [c_A(t) + \boldsymbol{\lambda}_{BC}\, c_C(t)]\, N(t)\, dt \quad (4)$$

$$X_C(t) = \int_0^t [\boldsymbol{\lambda}_{CA} c_A(t) - \boldsymbol{\lambda}_{CB}\, c_B(t)]\, N(t)\, dt \quad (5)$$

Let $P(X_A) = p(x_A)$, $x_A = X_A/N1$, be the probability that granule A collides with the granules B and C, then collected at the electrode, under well-defined conditions (nature and the size of the three classes of granules, the geometry of the fluidized bed, the air flow of the latter the fluidized bed, the high voltage applied to the electrodes, etc). The separated masses of the three materials during a period of time t are given by the following formulas:

$$M_{As}(t) = \int_0^t P(X_A(t))\, M_A(t)\, dt = \int_0^t P(x_A(t))\, M_A(t)\, dt \quad (6)$$

$$M_{Bs}(t) = \int_0^t P(X_B(t))\, M_B(t)\, dt = \int_0^t P(x_B(t))\, M_B(t)\, dt \quad (7)$$

$$M_{Cs}(t) = \int_0^t P(X_C(t))\, M_C(t)\, dt = \int_0^t P(x_C(t))\, M_C(t)\, dt \quad (8)$$

The probability $P(X_A)$ for a granule of material *A* to be separated is given by Gauss's law:

$$P(X_A) = \Pi((X_A - X_{Aav})/\sigma_{XA})$$
$$P(X_A) = \Pi((x_A - x_{Aav})/s_{xA}) = p(x_A) \quad (9)$$

Where: P is the standard normal distribution function. This expression can be rewritten as follows:

$$X_A(t) = (c_B + \lambda_{AC}\, c_C) N_1 t \quad (10)$$

Where: Π is the standard normal distribution function. This expression can be rewritten as follows:

$$P(X_A) = p(X_A) = \Pi\left(\frac{(c_B + \lambda_{AC}\, c_C)t - x_{Aav}}{s_{xA}}\right) \quad (11)$$

$$(1 - c_{A1})\, t_{50\%} - x_{Aav} = 0 \quad (12)$$

Where: $x_A = \frac{X_A}{N_1}, x_{Aav} = \frac{X_{Aav}}{N_1}, sx_A = \frac{s_{XA}}{N_1}$, and:

$$s_{xA} = x_{Aav}/2 \quad (13)$$

This value reflects the great dispersion of granules tribocharging conditions. By replacing in (10) the values of x_{Aav} and s_{xA}, , it is possible to have an estimation of $p(x_A)$. The probabilities $p(x_B)$ and $p(x_C)$ are calculated in the same way.

According to this model, if X_C (t) > 0, all the C particles are recovered in the collector B; if X_C (t) < 0, all the C particles are recovered into the collector A. There is also a percentage cair of the particles A, B and C in the fluidized bed which will be recovered accidentally in the two collectors because of air turbulence. The mass of A, Band C granules recovered in the collector due to this parasitic phenomenon can be calculated with the following formulas:

$$M_{Asair(B)}(t) = \int_0^t (c_{airA} \quad c_A(t))M(t)dt \qquad (14)$$

$$M_{Bsair(B)}(t) = \int_0^t (c_{airB} \quad c_B(t))M(t)dt \qquad (15)$$

$$M_{Csair(B)}(t) = \int_0^t (c_{airC} \quad c_C(t))M(t) \qquad (16)$$

In the industrial separator, specific to the operation of industrial plants, at each instant t there is a percentage $\mathbf{c_{op}= 1\%}$ of the mass of the particles ***A, B*** and ***C*** in the fluidized bed will be endowed by the particles of opposite polarity stuck on the surface electrodes.

The masses separated in this way of a product P (with ***P = A, B*** *or* ***C***), recovered in the collectors A and B up to time t, are denoted respectively $\boldsymbol{M_{P\text{-}A(op)s}(t)}$ and $\boldsymbol{M_{P\text{-}B(op)s}(t)}$. They are calculated with the formulas:

$$M_{A-B(op)}(t) = \int_0^t (c_{opA} \quad c_A(t))M_{Bs}(t)dt \qquad (17)$$

$$M_{B-A(op)}(t) = \int_0^t (c_{opB} \quad c_B(t))M_{As}(t)dt \qquad (18)$$

If x_C (t)> 0

$$M_{C-A(op)}(t) = \int_0^t (c_{opC} \quad c_C(t))M_{As}(t)dt \qquad (19)$$

If x_C (t)< 0

$$M_{C-B(op)}(t) = \int_0^t (c_{opC} \quad c_C(t))M_{Bs}(t)dt \qquad (20)$$

Using the assumptions cited above, if xC (t)> 0, the majority of the C particles are recovered in the collector B except for a few which will be recovered in the collector A($M_{(C\text{-}A(op)}$ (t)). If x_C (t) <0, the majority of particles C are recovered in collector A except for a few which will be recovered in collector B($M_{_(C\text{-}B(op)}$(t)), the instantaneous masses respectively recovered in collector A denoted $M_{coll(A)}(t)$ and in the manifold B denoted $M_{coll\ (B)}\ (t)$ are formulated as follows:

IF $x_C(t)> 0$:

$$M_{bac(-)}(t) = M_{As}(t) + M_{Asair(A)}(t) + M_{Bsair(A)}(t) + M_{Csair(A)}(t) + M_{C-A(op)}(t)M_{B-A(op)}(t) \qquad (21)$$

$$M_{bac(+)}(t) = M_{Bs}(t) + M_{Bsair(B)}(t) + M_{Cs}(t) + M_{Asair(B)}(t) + M_{Csair(B)}(t) + M_{A-B(op)}(t) \qquad (22)$$

But if $x_C(t)<0$:

$$M_{bac(-)}(t) = M_{As}(t) + M_{Cs}(t) + M_{Asair(A)}(t) + M_{Bsair(A)}(t) + M_{Csair(A)}(t) + M_{B-A_{(op)}}(t) \qquad (23)$$

$$M_{bac(+)}(t) = M_{Bs}(t) + M_{Csair(B)}(t) + M_{Bsair(B)}(t) + M_{Asair(B)}(t) + M_{A-B(op)}(t) + M_{C-B(op)}(t) \qquad (24)$$

III. SIMULATION ALGORITHM

An iterative algorithm can be employed for obtaining the estimation masses respectively recovered in collector A denoted $\boldsymbol{M_{coll(A)}(i)}$ and in the manifold B denoted $\boldsymbol{M_{coll\ (B)}\ (i)}$ are formulated as follows [12]:

Si $x_{Ce}(i)> 0$:

$$M_{bac(-)}(i) = M_{Ase}(i) + M_{Aseair(A)}(i) + M_{Bseair(A)}(i) + M_{Cse\ air(A)}(i)) + M_{B-Ae(op)}(i) + M_{C-Ae(op)}(i) \qquad (25)$$

$$M_{bac(+)}(i) = M_{Bse}(i) + M_{Cse}(i) + M_{Ase\ air(B)}(i) + M_{Bse\ air(B)}(i) + M_{Cse\ air(B)}(i) + M_{A-Be(op)}(i) \qquad (26)$$

If $x_{Ce}(i)<0$:

$$M_{bac(-)}(i) = M_{Ase}(i) + M_{Cse}(i) + M_{Ase\ air(A)}(i) + M_{Bse\ air(A)}(i) + M_{Cse\ air(A)}(i) + M_{B-A_{e(op)}}(i) \qquad (27)$$

$$M_{bac(+)}(i) = M_{Bse}(i) + M_{Ase\ air(B)}(i) + M_{Bse\ air(B)}(i) + M_{Cse\ air(B)}(i) + M_{A-Be(op)}(i) + M_{C-Be(op)}(i) \qquad (28)$$

Purities of products A and B are estimated from equations (29), (30) as follows

$$P_{Ae}(\%) = \left[(M_{Ase}(i) + M_{Ase\ air(A)}(i))/ M_{colle(A)}(i)\right].100 \qquad (29)$$

$$P_{Be}(\%)\left[(M_{Bse}(i) + M_{Bse\ air(B)}(i))/ M_{coll\ e(B)}(i)\right].100 \qquad (30)$$

IV. SIMULATION RESULTS

For this study, the algorithm presented in § 4 was applied. The calculations were performed with a program written in MATLAB 7.8. The iteration step is Δt=1s, the initial mass was taken M1=3000g (with MP=200g) and cop_A=1%; cop_B=1%; cop_C=1%. The values of x_{Aav}, s_{xA}, x_{Bav} and s_{xB} were chosen following the experimental procedure described in precedent works.

IV-1. Nature of the granular mixture

Fig. 2 corroborates the evolution of the mass recovered for two examples of the position of third material compared to the position of two other granules A and B in the tribo-electric series for a mixture of 33%***A***+33%***B***+33 %***C.***

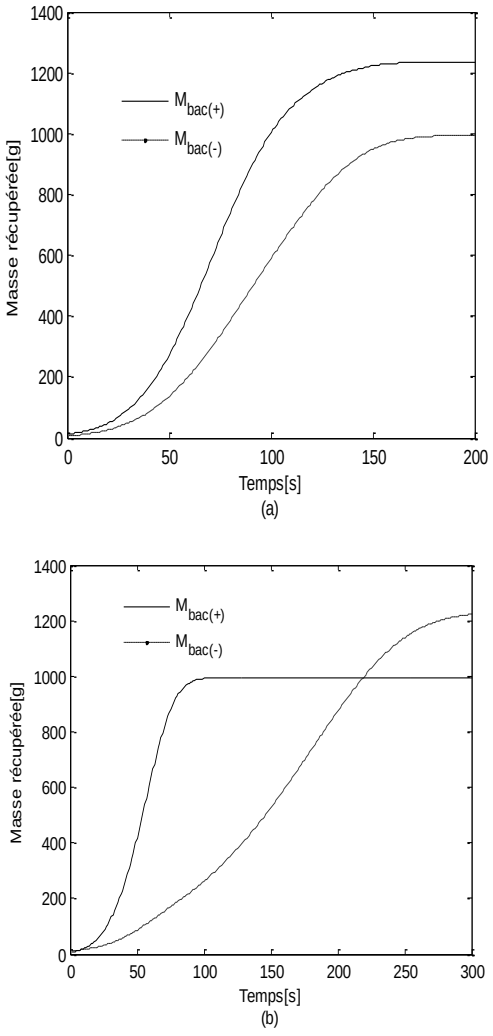


Fig. 2 Evolution of the estimated masses recovered in the two bins of the collector of an industrial tribo-aero-electrostatic separator for : *a)* λ_{AC}*=0,6;* λ_{BC}*=0,4; b)* λ_{AC}*=0,4;* λ_{BC}*=0,6*

a) ***C*** is between ***A*** and ***B***, closer to A in the triboelectric series, then $0 \leq \lambda_{AC} \leq 1$, $0 \leq \lambda_{BC} \leq 1$ with $\lambda_{AC} < \lambda_{BC}$ and $\lambda_{AC}+\lambda_{BC}=1$(all particles C will be collected with particles A).

b) ***C*** is between ***A*** and ***B***, closer to ***B*** in the triboelectric series, then $0 \leq \lambda_{AC} \leq 1$, $0 \leq \lambda_{BC} \leq 1$ with $\lambda_{AC} > \lambda_{BC}$ and $\lambda_{AC}+\lambda_{BC}=1$ (all particles C will be collected with particles B).

The fig 2 show the results of simulations for a tribo-aero-electrostatic device in intermittent regime, executed for two cases of the position of the granules ***C*** in the triboelectric series. Figure (2.a) illustrates the masses recovered in the two bin of the collector in the case where ***C*** being between *A* and B and closer to B in the triboelectric series. The charges exchanged between particles ***A***(or ***B***) and C are respectively λ_{AC}=0.6 and λ_{BC}=0.4. The ***B*** and ***C*** pellets collected in bin (+) are collected at a slightly faster rate than the ***A*** pellets collected in bin (-).

Fig.2 (b) of the masses recovered in the two bins of the collector in the case where C being between ***A*** and ***B*** is closer to ***A*** in the triboelectric series, the charges exchanged between the particles ***A*** (or ***B***) and ***C*** are respectively λ_{AC}=0.4 and λ_{BC}=0.6. Granules **C** are collected with Granules ***A*** in bin (-) are collected at a slightly faster rate than Granules ***B*** collected in bin (+).

IV-2. Composition of the granular mixture

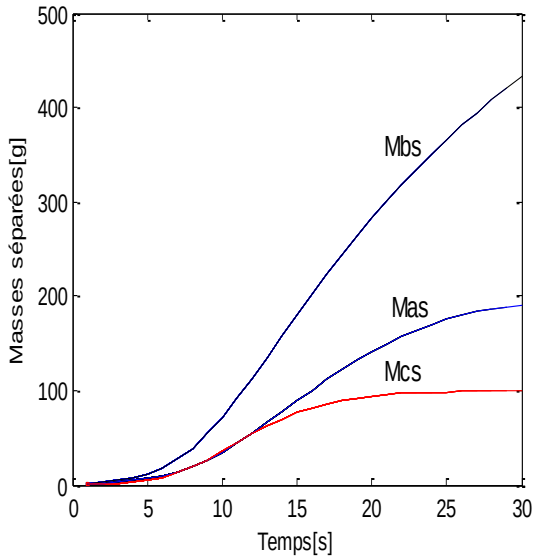
In this part, another program written in "MATLAB.7.0" was used. The iteration step is $\Delta t = 1$ s, the initial mass is M1 = 1000 g (with M_{lim} = 300 g). The masses Δ ***M As(i),*** Δ***MBs (i)*** *and* Δ***MCs (i)*** are represented by the curves in the following figure . In all cases, the granular mixture is considered to consist of 45% A+45% B+10%C and 1% Cop.

We notice in the figure (3-b) that the recovery of the particles ***B*** is more important, in this case ***C*** is between ***A*** and ***B*** closer to ***B*** therefore ***C*** will take care of the same sign as B. **Mbs** (i) obtained in the curve (about 440 g) represents the mass of the ***B*** and ***C*** particles collected in the ***B*** particle collector.

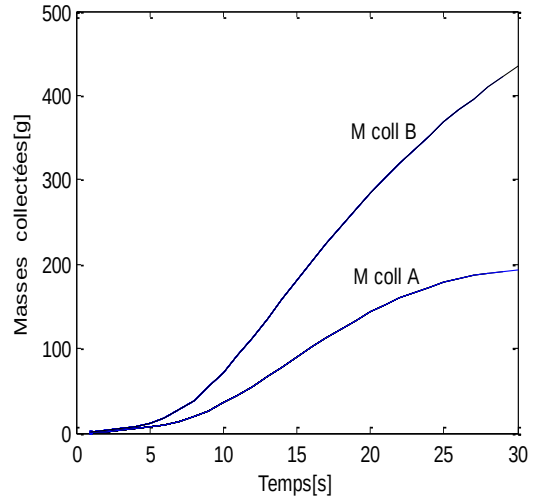
IV-3. Collected masses attracted by the particles of opposite polarity

In order to calculate the purties of the products collected in the compartments of the two collectors A and B in intermittent mode we must calculate

collected masses attracted by the particles of opposite polarity for a mass M=1000 g (M_lim=300g, $\lambda_{AC}=0,7$; $\lambda_{BC}=0,3$) after 30s of separation. The figures 4 (a), 4(b) and 4(c), represent the collected masses attracted by the particles of opposite polarity stuck on the surface of the electrodes, noted:



(a)



(b)

Fig. 3 Evolution of the estimated masses recovered in the two bins of the collector $\lambda_{AC}=0,7$; $\lambda_{BC}=0,3$
a) Separated masses, b) Collected masses

M A.A op(t):mass of **A** attracted by the particles of opposite polarity stuck on the surface of the electrodes and collected in the collector **A**

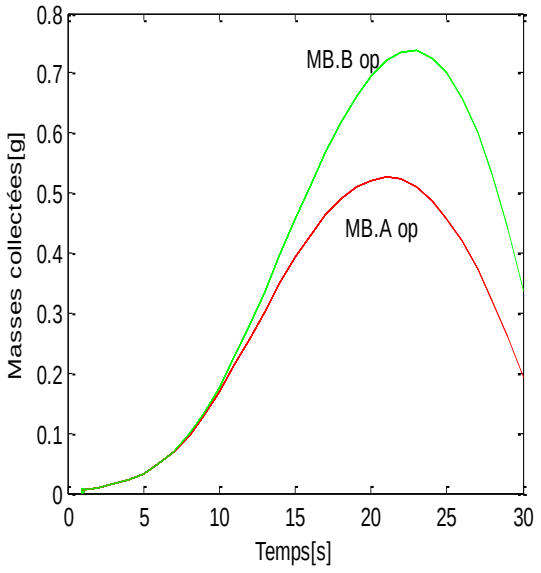
M A.B op(t):mass of **A** attracted by the particles of opposite polarity stuck on the surface of the electrodes and collected in the collector **B**

M B.A op(t): mass of **B** attracted by the particles of opposite polarity stuck on the surface of the electrodes and collected in the collector **A**

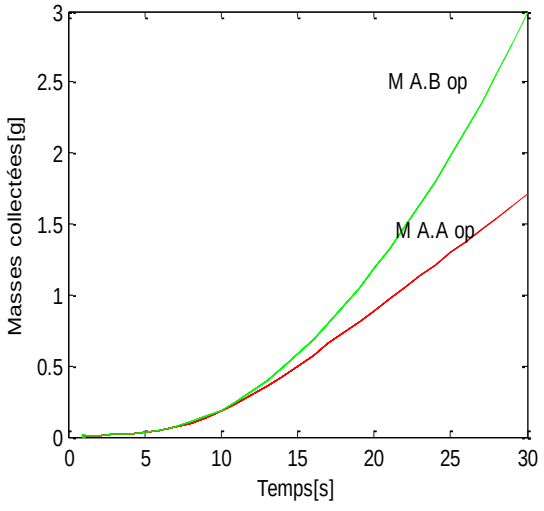
M B.B op(t):mass of **B** attracted by the particles of opposite polarity stuck on the surface of the electrodes and collected in the collector **B**

M C.A op(t):mass of **C** attracted by the particles of opposite polarity stuck on the surface of the electrodes and collected in the collector **A**

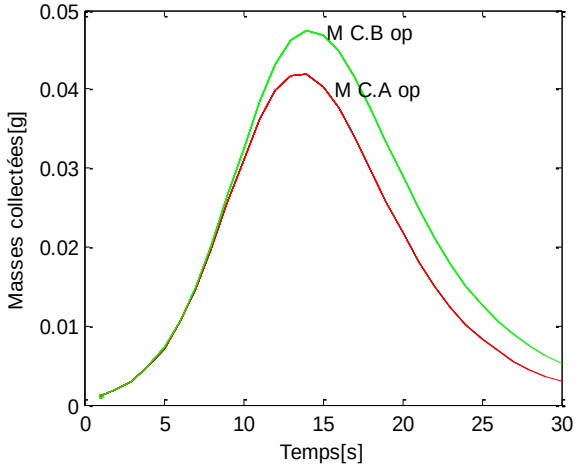
M C.B op(t): mass of **C** attracted by the particles of opposite polarity stuck on the surface of the electrodes and collected in the collector **B**



(a)



(b)



(c)

Fig. 4 collected masses attracted by the particles of opposite polarity stuck on the surface of the electrodes for : $\lambda_{AC}=0,7$; $\lambda_{BC}=0,3$.

The results of numerical calculations showed that the operation of a tribo-aero-electrostatic separator in intermittent regime can be accurately predicted by numerical simulation, based on a simple mathematical model.

V. CONCLUSION

Numerical simulations indicate that the operation of the separator depends on:

- The composition of the mixture and the nature of the separated materials. The minority particles charge faster and they are easily separated from the mixture, while the majority particles need more time to be sufficiently charged and carried towards the collectors.
- The distribution of the three kinds of granules in the two collectors is linked to their respective positions in the tribo-electric series. The sign of the charge acquired by the two materials which are close in this series is the same, therefore these materials will be collected in the same collector.
- The presence of three classes of particles collected under the effect of the air flow in the two collectors depends on the volume density of the granules to be separated. The lighter ones can be more easily led into the wrong compartment and in addition the presence of particles attracted by the charged particles of opposite sign and stick on the electrodes has carpet which justifies the presence of impurities in the two collector tanks

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