Numerical Simulation of the Continuous Operation of a Tribo-aero-electrostatic Separator for Mixed Granular Solids

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Abstract **– Numerical simulation has proved to be a powerful tool in the research and development of new electrostatic processes. In a previous paper, the authors have introduced a simple mathematical model for simulating the outcome of a novel tribo-aero-electrostatic separation process for binary mixtures of granular materials. The mathematical model assumed that the probability of a granule to be separated can be expressed as a function of the number of impacts with granules belonging to the other class of materials. The process is characterized by the fact that the charging of the granules is produced in a fluidized bed device, in the presence of an electric field. The aim of the present paper is to simulate the continuous operation of such a device at various feed rates. The evolution in time of the mass of granules collected at the electrodes has been computed for various compositions of the granular mixture. The effect of the walls and the presence of a third species of particles were taken into account. The computed results were in good agreement with the experiments. They demonstrate that open-loop continuous operation of the separator is possible for a range of feed-rates that depends on the composition of the materials to be separated.**

Index Terms **-- electrostatic separation, granular materials, numerical techniques, triboelectricity**

I. Introduction

Since the start of the industrial scale production of synthetic polymers in the 1940s, the generation rate of plastic solid wastes has increased considerably. The recycling of such wastes has become a major environmental issue [1]. None of the current available technologies of separating mixed plastics is entirely satisfactory. This explains the considerable research effort that is made for the development of novel dry processes that would enable the separation of at least part of these plastics, so that to contribute towards a more effective use of primary resources [2-3].

Some of the existing electrostatic separation technologies for mineral ores [4-6] have already found application in the separation of plastics. These technologies involve, as a first and most delicate operation, the triboelectric charging of the constituents of the granular mixture [7-9], followed by their separation in the electrostatic field generated by a system of high-voltage electrodes. The positively- and negatively-charged fractions are recovered in distinct compartments of a collector [10-12].

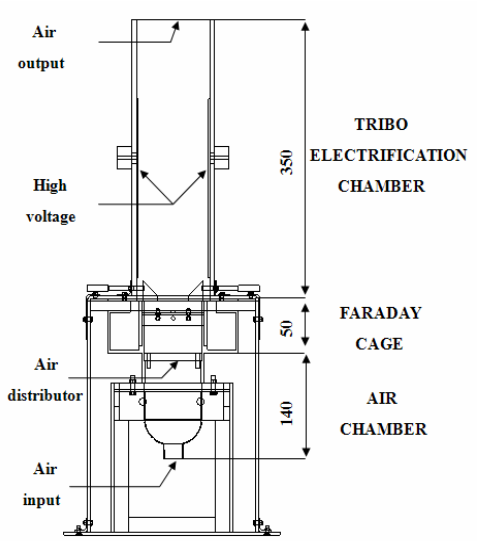


Fig. 1. Schematic representation of the tribo-aero-electrostatic separator.

The wider use of these technologies is hampered by the non-homogeneity of the charge acquired by the granules: some do not carry enough charge to be separated by the electric field forces. A recently-patented tribo-aero-electrostatic separation process for mixed granular plastics [13, 14] gives an original solution to this problem: the tribo-charging is produced in a parallelepiped fluidized bed device, in the presence of an electric field (Fig. 1). This field, perpendicular to the direction of the fluidization air, is generated by two electrodes glued to opposite walls of the tribocharging chamber and energized from two DC high-voltage supplies of opposite polarities. Thus, the granules in the fluidized bed cannot leave the tribocharging zone unless they are enough charged to be attracted to the electrodes.

Numerical simulation techniques already been employed to achieve the optimization of role-type electrostatic separators for the recycling of metallic and insulating particles from cable wastes [15, 16]. In that case, numerical models have been proposed for estimating the charge acquired by the particles and for calculating their trajectories in an electric field [17-19]. The simulations pointed out the effects of the various process control variables: high- voltage, roll-speed, etc.

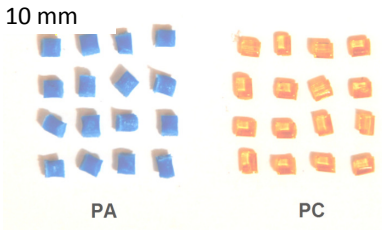


Fig. 2. Aspect and size of the polyamide (PA) and polycarbonate (PC) particles employed in this study.

Tribo-charging is a much more complex phenomenon [20-23] and its mathematical modeling is still in progress [24-29]. The computation of particle trajectories, by taking into account all the mechanical, aerodynamic and electrical forces is a very complicated and time-consuming task. Both researchers and practitioners need a more user-friendly simulation tool for performing the feasibility studies that precede the development of a new application.

In a previous work, a simple mathematical model for simulating the outcome of the tribo-aero-electrostatic separation process for binary mixtures of granular plastics was developed [30]. However, the analysis was simplified by assuming that the process works with samples of constant mass. Therefore, the aim of the present work is to develop a mathematical model for simulating a continuously-operating industrial process, where the granular mixture to be separated is introduced in the fluidized bed at a constant rate.

II. Experimental Procedure

The tribo-electrostatic separation experiments were performed on blue virgin polyamide (PA) and orange polycarbonate (PC) granules, used in the plastics industry. The samples were prepared as binary mixtures with different compositions. The experiments were carried out at fixed air velocity v = 6 m/s under relatively stable ambient conditions: temperature T = 17 - 22°C, relative humidity RH = 44 - 60%.

The experimental device (Fig. 1) consisted in a rectangular prism chamber (115 mm × 85 mm × 400 mm), with two opposite vertical walls made of polycarbonate (PC), the other two consisting in aluminum plates connected to two adjustable DC high-voltage supplies of positive and negative polarity (model ES60P-20W and ES60N-20 W, Gamma HV Research Inc., Ormond Beach, FL). The fluidization air is introduced through a perforated plate at the bottom of the chamber. The granules deposited on this plate are dispersed by the ascending air in the tribocharging chamber, where multiple granule-granule and some granule-wall collisions take place [14]. The charged granules are attracted to the electrodes of opposite polarity and fall into the two collecting hoppers. The instantaneous mass of the collected products is measured every Δt =1 s with electronic balances (resolution: 0.01 g), connected to a data acquisition system [14].

Table I. Main Characteristics of the Granular Materials Employed in this Study

Granule	PA	PC
Color	Blue	Orange
Form	Quasi cylindrical	Quasi cylindrical
Typical Size [mm]	Ø 2.7 x 3.4	Ø 2.9 x 3.5
Average mass [mg]	21	24

III. Mathematical Model

The study is focused on the separation of a binary mixture of granular materials, denoted A and B. The two classes of granules have similar size and mass density, but different tribocharging characteristics.

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 with granules belonging to the other class of materials and with the walls of the fluidized bed. The number of such collisions depends on the concentration of each class of materials in the granular mixture.

The effect of the granules-to-wall collisions is similar to the presence of a third type of granules in the fluidized bed. Thus, in order to take into account both type of collisions, the total mass $M(t)$ of the materials processed at an instant t is expressed as :

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

where $M_A(t)$ and $M_B(t)$ are the masses of the two classes of granules; M_W is the fictitious mass of the walls, which is constant in time. Under these circumstances, the respective concentrations of the materials A, B and W are:

$$c_A(t) = M_A(t)/M(t), \; c_B(t) = M_B(t)/M(t), \; c_W = M_W/M(t) \quad (2)$$

In a fluidized bed of known geometry and air velocity, each granule experiences $N(t)$ collisions per unit time. At t = 0, $N(0) = N_1$. The charge exchange in each granule-to-wall collision is different than in the case of a contact between two granules, as it depends on the relative position of the wall material W and of the two materials A and B in the triboelectric series. If a unit of adimensional charge were exchanged in a collision between two granules A and B, the adimensional charge exchanged between a granule A (or B) and the wall would be λ_A (respectively λ_B). There are several situations that can be encountered in practice:

(i) W is between A and B in the triboelectric series, then $0 \le \lambda_A \le 1$, $0 \le \lambda_B \le 1$ (the granule-to-wall collisions have less effect than those between two granules);

(ii) B is between A and W, then $\lambda_A > 1$ (an A granule charges better in a collision with the wall W than with a B granule), and $\lambda_B < 0$ (the charge B exchanges with the wall has an opposite sign than that exchanged with A);

(iii) A is between B and W, then $\lambda_B > 1$ (a B granule charges better in a collision with the wall W than with an A granule), and $\lambda_A < 0$ (the charge A exchanges with the wall has an opposite sign than that exchanged with B);

Thus, during a time period t, the number of unit adimensional charges exchanged by an A granule is:

$$X_A(t) = \int_0^t [c_B(t) + \lambda_A c_W(t)] N(t)\, dt \quad (3a)$$

Similarly, the number of unit adimensional charges exchanged by each B granule can be expressed as:

$$X_B(t) = \int_0^t [c_A(t) + \lambda_B c_W(t)] N(t)\, dt \quad (3b)$$

Let $P(X_A)= p(x_A)$, with $x_A = X_A/N_1$, be the probability for an A granule to be collected at the electrode after exchanging $X_A(t)$ unit adimensional charges, under well-defined operating conditions (nature and size of the two classes of granules, geometry of the fluidized bed, fluidized air pressure, high-voltage applied to the electrodes, etc). The probability $P(X_A)$ can be assumed to be given by Gauss's law

$$P(X_A) = \Pi((X_A - X_{Aav})/\sigma_{xA}) \quad (4)$$

where Π is the standard normal distribution function, X_{Aav} designates the average value and σ_{xA} the standard deviation. This expression can be reformulated as follows:

$$P(X_A) = \Pi((x_A - x_{Aav})/s_{xA}) = p(x_A) \quad (5)$$

where: $x_A = X_A/N_1$; $x_{Aav} = X_{Aav}/N_1$; $s_{xA} = \sigma_{xA}/N_1$. Similar formulas can be written for a B granule, and the masses of materials separated up to any instant t are:

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

$$M_{Bs}(t) = \int_0^t P(X_B(t))M_B(t)dt = \int_0^t p(x_B(t))M_B(t)dt \quad (6b)$$

IV. Simulation Algorithm

An iterative algorithm can be employed for obtaining the estimation $X_{Ae}(i,j)$ of the number of unit adimensional charges exchanged at step j by the granules introduced in the fluidized bed at step i, the estimation $M_{Ase}(j)$ of the separated mass $M_{As}(t)$, at $t = j\,\Delta t$, where i and j are positive integer and Δt is sufficiently small for the mass $M_A(t)$, the concentration $c_A(t)$ and the collision frequency $N(t)$ to be considered constant:

$$M_{Ae}(k) = M_A((k\text{-}1).\Delta t), \quad (7a)$$

$$c_{Ae}(k) = c_A((k\text{-}1).\Delta t), \quad (7b)$$

$$N_e(k) = N((k\text{-}1).\Delta t) \quad (7c)$$

in any interval $(k-1)\Delta t \le t < k\,\Delta t$, $k = 1, 2, \ldots, j$.

Step 1: The estimated number of unit adimensional charges exchanged by each A granule can be computed from (3a) as follows:

$$X_{Ae}(1,1) = [c_B(0) + \lambda_A c_W]N(0) \quad (8)$$

With $x_{Ae}(1,1) = X_{Ae}(1,1)/N(0)$, the estimated mass $M_{Ase}(1)$ of the A granules separated at Δt is obtained from (6a):

$$M_{Ase}(1) = p(x_{Ax}(1,1))\, M_{Ae}(1) = p(x_{Ae}(1,1))\, m_{Ae}(1,1) \quad (9)$$

Similarly:

$$X_{Be}(1,1) = [c_A(0) + \lambda_B c_W]N(0) \quad (10)$$

where $x_{Be}(1,1) = X_{Be}(1,1)/N(0)$, and the estimated mass $M_{Bse}(1)$ of B granules separated at Δt is calculated as follows:

$$M_{Bse}(1) = p(x_{Be}(1,1))\, M_{Be}(1) = p(x_{Be}(1,1))\, m_{Be}(1,1) \quad (11)$$

where $m_{Ae}(1,1) = M_A(0)$ and $m_{Be}(1,1) = M_B(0)$ are the initial masses at $t = 0$. Remaining masses after the first step are calculated from the initial mass:

$$m_{Ae}(1,2)=m_{Ae}(1,1)- p(x_{Ae}(1,1))\, m_{Ae}(1,1) \quad (12a)$$

$$m_{Be}(1,2)=m_{Be}(1,1)- p(x_{Be}(1,1))\, m_{Be}(1,1) \quad (12b)$$

In the above formulas, $m_{Ae}(1,2)$ and $m_{Be}(1,2)$ are the particles that have experienced collisions in the first step and are going to undergo further collisions during the second iteration. Therefore, their probability of separation is greater compared to the new particles that will be introduced into the fluidized bed at the next step.

Step j ($j \ge 2$): Let $m(j,j)$ be the mass m added at each step j:

$$m_e(j,j)=m;\ m_{Ae}(j,j)=m_A;\ m_{Be}(j,j)=m_B \quad (13)$$

where $m_{Ae}(j,j)$ and $m_{Be}(j,j)$ are the masses of the new granules introduced into the fluidized bed. The total mass of A granules in the fluidized bed at step j can be expressed as:

$$M_{Ae}(j)= \sum_{i=1}^{j} m_{Ae}(i,j) \quad (14)$$

A similar formula can be written for $M_{Be}(j)$. The total estimated mass at step j is:

$$M_e(j) = M_{Ae}(j) + M_{Be}(j) + M_W \quad (15)$$

The masses $m_{Ae}(i,j)$ and $m_{Be}(i,j)$ that entered at step i and still present in the fluidized bed at the beginning of step j are calculated separately:

$$m_{Ae}(i,j)= m_{Ae}(i,j\text{-}1) - m_{Ae}(i,j\text{-}1) * p(x_{Ae}(i,j\text{-}1)) \quad (16a)$$

$$m_{Be}(i,j)= m_{Be}(i,j\text{-}1) - m_{Be}(i,j\text{-}1) * p(x_{Be}(i,j\text{-}1)) \quad (16b)$$

The concentrations $c_{Ae}(j)$ and $c_{Ae}(j)$ of the A and B granules can be determined from (2), using the estimates $M_{Ae}(j)$ and $M_{Be}(j)$ of the masses of the two materials in the fluidized bed:

$$c_{Ae}(j) = M_{Ae}(j) / M(j) \quad (17a)$$

$$c_{Be}(j) = M_{Be}(j) / (M(j) \quad (17b)$$

Let:

$$x_{Ae}(i,j) = X_{Ae}(i,j)/N(0),\ x_{Be}(i,j) = X_{Be}(i,j)/N(0) \qquad (18)$$

With these notations, the normalized unit adimensional charges exchanged by the A and B granules of the initial masses $m_{Ae}(1,1)$ and $m_{Be}(1,1)$ in the fluidized bed up to the instant $t = j\Delta t$ can be expressed as follows:

$$x_{Ae}(1,j)= \{[c_{Be}(1)+\lambda_A\, c_{We}(1)] + [c_{Be}(2)+\lambda_A\, c_{We}(2)]M_e(2)/M_e(1) \\ \ldots + [c_{Be}(j) +\lambda_A\, c_{We}(j)]M_e(j)/M_e(1)\}\Delta t \qquad (19a)$$

$$x_{Be}(1,j)= \{[c_{Ae}(1)+\lambda_B\, c_{We}(1)] + [c_{Ae}(2)+\lambda_A\, c_{We}(2)]M_e(2)/M_e(1) \\ \ldots + [c_{Ae}(j) +\lambda_B\, c_{We}(j)]M_e(j)/M_e(1)\}\Delta t \qquad (19b)$$

The new particles introduced at each time step Δt have the possibility to get charged starting with step j:

$$x_{Ae}(j,j)= \{[c_{Be}(j) +\lambda_A\, c_{We}(j)]M_e(j)/M_e(1)\}\ \Delta t \qquad (20a)$$
$$x_{Be}(j,j)= \{[c_{Ae}(j) +\lambda_B\, c_{We}(j)]M_e(j)/M_e(1)\}\ \Delta t \qquad (20b)$$

More generally:

$$x_{Ae}(i,j) = \{[c_{Be}(i)+\lambda_A c_{We}(i)]M_e(i)/M_e(1)+ \\ [c_{Be}(i+1)+\lambda_A c_{We}(i+1)]M_e(i+1)/M_e(1)+\ldots \\ [c_{Be}(j)+\lambda_A c_W(j)]\ M_e(j)/M_e(1)\}\Delta t \qquad (21a)$$

$$x_{Be}(i,j) = \{[c_{Ae}(i)+\lambda_B c_{We}(i)]M_e(i)/M_e(1)+ \\ [c_{Ae}(i+1)+\lambda_B c_{We}(i+1)]M_e(i+1)/M_e(1)+\ldots \\ [c_{Ae}(j)+\lambda_B c_W(j)]\ M_e(j)/M_e(1)\}\Delta t \qquad (21b)$$

Consequently, the estimated masses of A and B granules separated at a step j is obtained from (6a):

$$\Delta M_{Ase}(j) = p(x_{Ae}(1,j))\ m_{Ae}(1,j) + p(x_{Ae}(2,j))\ m_{Ae}(2,j) + \ldots \\ + p(x_{Ae}(i,j))\ m_A(i,j) \qquad (22a)$$
$$\Delta M_{Bse}(j) = p(x_{Be}(1,j))\ m_{Be}(1,j) + p(x_{Be}(2,j))\ m_{Be}(2,j) + \ldots \\ + p(x_{Be}(i,j))\ m_B(i,j) \qquad (22b)$$

IV. Numerical Simulation Results

The calculations were carried out with a program written in MATLAB 7.0. The iteration step was Δt = 1 s, the initial mass was taken M_1 = 200 g (with M_W = 30 g) and the mass $m(j,j)$ introduced at each step was assumed to be 6 g/s. The values of x_{Aav}, s_{xA}, x_{Bav}, s_{xB} were chosen following the procedure and based on the experimental data presented in a previous paper [30]. The walls of the tribocharging device were supposed to be made of a material situated in between A and B in the triboelectric series ($\lambda_A = 0.6$, $\lambda_B = 0.4$).

The masses $\Delta M_{Ase}(j)$ and $\Delta M_{Bse}(j)$ separated at each step j were estimated with (22a) and (22b) and represented in Figs. 3a and 4b, for two granular mixtures: 50% A + 50% B and 30% A + 70% B, respectively. For the samples containing 50% of each product, the slight difference between the separated masses of A and B (Fig. 3b) is due to the different effect of the granule-to-wall collisions ($\lambda_A > \lambda_B$). After a transient regime that lasts less than 30 s, the process attains a stable operation: the estimated values of the masses separated in any unit of time are equal to the feed rate.

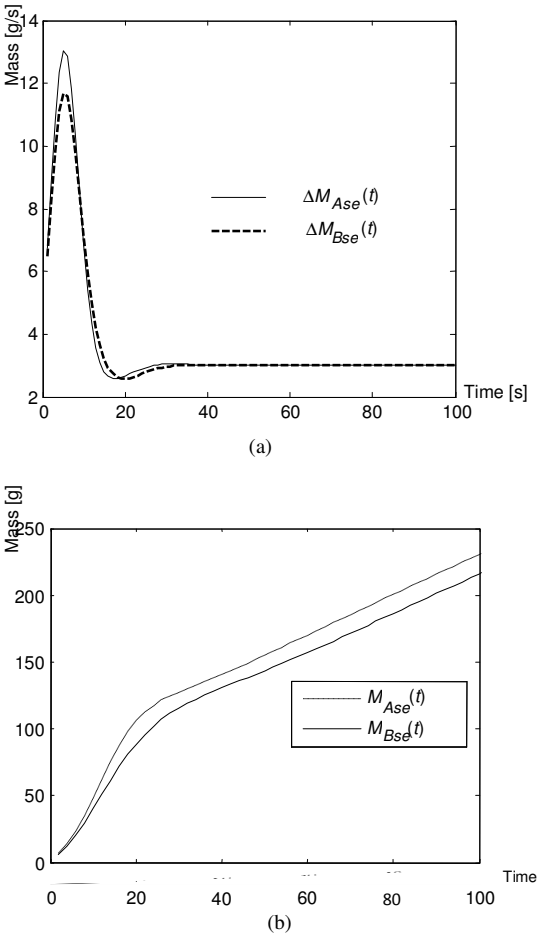
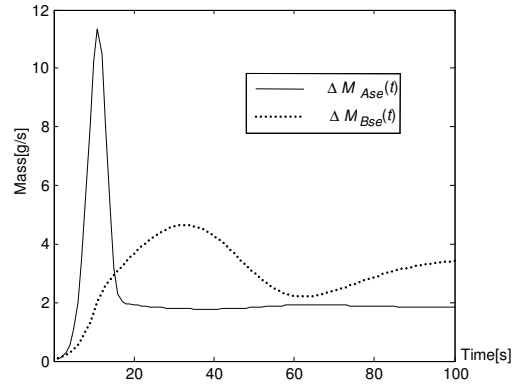


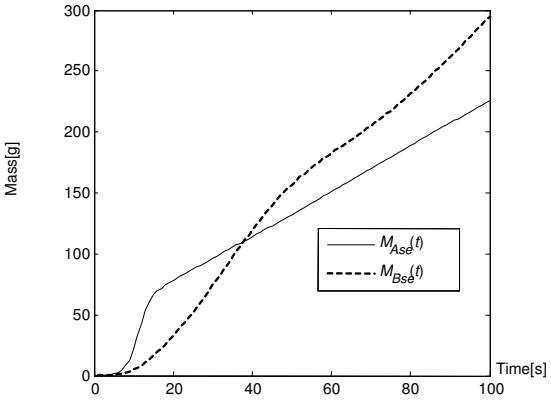
Fig. 3. Separated mass $\Delta M_{Ase}(j)$ and $\Delta M_{Bse}(j)$ at each time step j (a) and total masses $M_{Ase}(j)$ and $M_{Bse}(j)$ (b), estimated for the case of a 50% A + 50% B granular mixture, the initial mass and the feed rate being respectively M_1 = 200 g and m (j, j) = 6 g/s.

In the case of the 30% A + 70% B granular mixtures, the stable operation is attained after a longer transitory regime: about 3 min (Fig. 4). At first, the A granules, which are in minority, are separated at a much faster rate then the B granules, as they have more opportunities to exchange charges by collisions with bodies of different nature. However, in less than 20 s the output rate of A granules slows down to a value that slightly oscillates around the value of their feed rate (i.e., 6 [g/s] x (30/100) = 1.8 [g/s]).

The output rate of B granules slowly increases during the first 30 s to attain a maximum close to 5 g/s, then – after a couple of oscillations of smaller amplitude – stabilizes at a value imposed by the feed rate (i.e., 6 [g/s] x (70/100) = 4.2 [g/s]). The balance between the input and output rates guarantees that the mass of material in the fluidized bed is maintained quasi-constant. This is a very important practical conclusion: no feed-back is necessary to keep the separation process under control.



(a)



(b)

Fig. 4. Separated mass $\Delta M_{Ase}(j)$ and $\Delta M_{Bse}(j)$ at each time step j (a) and total masses $M_{Ase}(j)$ and $M_{Bse}(j)$ (b), estimated for the case of a 30% A + 70% B granular mixture, the initial mass and the feed rate being respectively M_1 = 200 g and m (j, j) = 6 g/s.

These predictions are confirmed by the experimental results given in Fig. 5. The curves recorded by the virtual instrument are similar to those obtained by numerical simulation. The minor discrepancies that can be detected between the experimental and simulated curves are due to the fact that part of the parameters employed for the numerical computations were obtained from a slightly different experiment described elsewhere [30].

V. Conclusions

(1) The continuous operation of a tribo-aero-electrostatic separator can be accurately predicted by numerical simulation, based on a simple mathematical model

(2) The operation of the separator depends on the composition of the mixture. The granules that are in minority get charged faster and are easily separated from the mixture, while the majority granules have to spend a longer time in the fluidized bed prior to being collected at the electrodes.

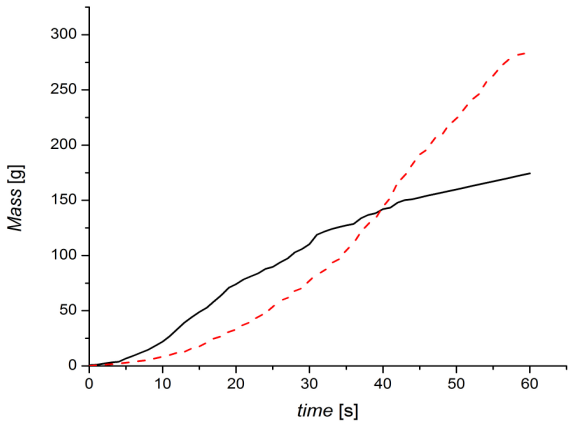


Fig. 5. Experimentally recorded instantaneous values of the masses of PA (solid line) and PC(dotted line) granules collected at the two electrodes (composition of the granular mixture: 30% PA + 70% PC)

(3) However, no matter what is the composition of the granular mixture, no feed-back is necessary to maintain the process under control, as the stabilized operation is easily attained in open-loop operation: after a short transitory regime, the output rate becomes equal to the input rate.

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