Physical model of granule adhesion to the belt-electrodes of a tribo-aero-electrostatic separator

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Abstract. Recent studies have demonstrated the effectiveness of tribo-aero-electrostatic separation technologies, which consist in the selective sorting of mixed granular insulating materials in a fluidized bed affected by an electric field orthogonally oriented to the direction of the fluidization air. The aim of the present paper is to put the theoretical bases for the optimization of this process, i.e. maximize the total mass of the granules collected at the two electrodes that generate the electric field. The various forces that drive a granule of given mass and electric charge through the electric field and make it stick to an electrode are expressed as functions of the several input variables and parameters of the process, such as the applied high-voltage or the surface roughness, the size and the position of the electrodes. The concepts of “critical electrostatic field” and “virtual climbing distance” are introduced. The prediction of the theoretical model are confirmed by the results of three sets of experiments, carried out on samples of a granular mixture consisting of 50% Acrylonitrile Butadiene Styrene (ABS) and 50% High Impact Polystyrene (HIPS), originating from the recycling of waste electric and electronic equipment. Higher separation efficiency was obtained when the electric field in the active zone was intensified by the use of an additional electrode connected to the ground and when the collecting electrodes were covered by a thin insulating layer.

1. Introduction
The tribo-electrostatic separation has been widely studied in view of many different industrial applications [1-3], including the recycling of granular plastic wastes [4-6]. A novel tribo-aero-electrostatic separator was designed [7] to avoid the drawbacks of classic tribo-charging separation by the simultaneous usage of triboelectricity, Coulomb force and electric image force [8]. In such a device, the granule charging and separation process takes place in a fluidized bed affected by an electric field orthogonal to the direction of the fluidization air.

The main parts of a tribo-aero-electrostatic separator are (figure 1): an air-flow chamber, a separation chamber and two collecting systems. The walls of the air-flow and separation chambers are made of transparent insulating boards, to facilitate the observation of the phenomena. A fine insulating mesh (air
A diffuser separates the two chambers and prevents the particles from falling into the air ducts.

![Diagram of tribo-aero-electrostatic separator](image)

**Figure 1.** The standard structure of tribo-aero-electrostatic separator.

Each of the two collecting mechanical structures is composed of a metal-belt conveyor, a protection plate, a brush and a collector. The metal belts are also the electrodes of the installation, as they are connected to two DC high-voltage power supplies of opposite polarities, and generate an electric field across the separation chamber. The protection plates are made of insulating materials to secure the operators and guide the particles fell into the collectors. The brushes are set close to the bottom edge of two electrodes in order to remove the charged granules that would otherwise remain stuck to the metal belts. A vibratory feeder introduces the granules in the separation chamber from the top of it. The free-falling granules are affected by the upwards-directed fluidization air flow. The collisions that occur between the granules in the mixture represent the main tribo-charging mechanism [9-11].

The electrodes generate electric field that is quasi-orthogonally-oriented to the direction of the fluidization air. Under the action of the Coulomb force, the charged granules are driven to the surface of the belt electrodes. The well-charged ones will stay pinned onto the surface of the electrodes by the electric field and image forces, and move along with the metal conveyors; the poorly-charged granules would rebound at the impact with the electrodes and fell back into the fluidized bed. They stay there until they get enough charged to be collected at the electrodes.

The factors that might influence the efficiency of tribo-electrostatic separation process have been estimated using the experimental design methodology [12, 13]. The experiments and the numerical simulations pointed out that the separation can be optimized by adjusting the control variables of the process, such as the high voltage or the speed of the fluidization air [14-16].

The aim of the present paper is to establish a physical model that would take into account the various forces that act on the charged granules, drive them through the electric field and make them stick to the electrodes. This model can be used to optimize the design of a novel tribo-aero-electrostatic separator.
2. Physical model

The electrostatic separation is produced by the simultaneous action of various electrical and mechanical forces. The former depend on the local intensity of the electric field. Therefore the first step in the elaboration of a physical model of granule behavior in an electrostatic separator consists in the computation of the electric field.

2.1. Electric field computation

Figure 2 (a) shows the distribution of electrostatic field between two vertical parallel plate electrodes, distanced at \( d_0 \) and energized from two high voltage supplies of opposite polarities \( \pm U \). The electrostatic field lines are perpendicular to the parallel plates and the strength \( E \) of the uniform electric field at the surface of plates can be computed as:

\[
E = \frac{2U}{d_0} \quad (1)
\]

In case that the electrodes make an angle \( \theta \) with the vertical plane as shown in figure 1, the electric field at the surface of electrodes cannot be computed with (1). Each field line can be approximated by a segment of length \( d_0 \) and two arcs of length \( d^* \), as shown in figure 2 (b). The distance \( d^* \) is computed as:

\[
d^* = \left(\frac{\theta}{360}\right) \times 2\pi R \quad (2)
\]

where \( R \) is the radius of the arc.

As shown in figure 3, the length \( d_L \) of the electrostatic field line corresponding to the point \((x_L, y_L)\) can be computed from (2), with \( R = L \):

\[
d_L = d_0 + 2d^* = d_0 + \left(\frac{\theta}{90}\right) \times \pi L \quad (3)
\]

The electrodes being supplied with symmetrical high-voltages of opposite polarities \( \pm U \), the electrostatic field \( E_L \) at the position of \((x_L, y_L)\) can be computed approximately as:

\[
E_L = \frac{2U}{d_L} = \frac{180U}{(90d_0 + \pi L)} \quad (4)
\]
Figure 3. Geometry of non-parallel electrodes system.

Figure 4. The repartition of the electric field strength $E$ as function of the distance $L$ at the surface of the metal belt electrodes, for three values of the angle $\theta$.

Figure 4 shows the repartition of the electric field strength $E$ at the surface of the electrode. Because the electrodes are inclined at an angle $\theta$, the electric field at their top edge $L_{top}$ is weaker than at $L = 0$ (i.e., at the bottom edge of the electrodes). The decay of the electric field strength $E$ along the electrode length is steeper for $\theta = 30^\circ$ than for $\theta = 20^\circ$ or $\theta = 10^\circ$. 
2.2. Forces analysis

The physical model is established for granules that are assumed to be perfect insulating spheres of radius $r$ and specific mass $\rho$, carrying a charge $Q$ uniformly distributed on their surface. This means that $Q$ can be considered as being concentrated in the center of the sphere. When compared with the distance $d_L$ (figure 3), the radius of sphere can be neglected and the granules can be represented as mechanical points of constant charge $Q$. The space between the electrodes is homogeneous and isotropic, of permittivity $\varepsilon_0$.

As shown in figure 5, the belt electrode moves at a constant speed $v$. A charged granule is attracted to the electrode and got in contact with it. The collision is assumed to be perfectly plastic (i.e., there is no granule rebound after the impact). As a consequence, the charged granules stick to the electrodes and move with them as long as the mechanical and electrical forces acting on it satisfy the condition:

$$G \times \cos(\theta) \leq \left[ G \times \sin(\theta) + F_i + F_e \right] \times \mu_{\text{max}}$$  \hspace{1cm} (5)

where $G$ is the weight of particle:

$$G = \left( \frac{4}{3} \pi r^3 \right) \rho g$$  \hspace{1cm} (6)

$F_i$ is the electric image force:

$$F_i = \frac{Q^2}{4\pi \varepsilon (2r)^2}$$  \hspace{1cm} (7)

$F_e$ is the electric field (Coulomb) force:

$$F_e = QE$$  \hspace{1cm} (8)

With $g = 9.81 \text{ m s}^{-2}$, $\varepsilon = 1.5/(4\pi 9 \times 10^9)$ and $\mu_{\text{max}}$ is the maximum coefficient of static friction between the granule and the electrode.

**Figure 5.** Schematic representation of particle adhesion to the surface of the electrode.
The above condition can be rewritten as:

\[
\frac{4\pi^3}{3} \rho g \cos(\theta) \leq \left( \frac{4\pi^3}{3} \rho g \sin(\theta) + Q^2 \left[ 4\pi \varepsilon (2r)^2 \right] + QE \right) \times \mu_{\max}
\]

(9)

Hereafter, the left and right members of (9) will be designated as:

\[
Y_1 = \left( \frac{4\pi^3}{3} \rho g \cos(\theta) \right)
\]

(10)

\[
Y_2 = \left( \frac{4\pi^3}{3} \rho g \sin(\theta) + Q^2 \left[ 4\pi \varepsilon (2r)^2 \right] + QE \right) \times \mu_{\max}
\]

(11)

The function \(Y_1\) is constant for granules of given size \(r\) and mass density \(\rho\), attached to an electrode inclined at a well-defined angle \(\theta\). As shown in figure 4, for any angle \(\theta > 0^\circ\), the electric field strength \(E\) decreases while the granules get closer to the upper edge of the belt electrode. To ensure the balance between \(Y_1\) and \(Y_2\) in a given point \(A\) (figure 5) and for a well-defined value of the coefficient of static friction \(\mu_{\max}\), the local electric field should have the minimum value \(E_{\min}\) computed from (4) and (9):

\[
E_{\min} = \frac{\left[ G \times \cos(\theta) / \mu_{\max} \right] - G \times \sin(\theta) - F_i}{Q}
\]

(12)

If the electric field strength \(E\) in any point at the surface of the electrode is higher than the critical electrostatic field \(E_{\min}\), the charged granule will pass over the top of the belt and will be collected in an appropriate compartment. Otherwise (i.e. \(Y_2 < Y_1\)), the granule will slide down and fall back into the fluidization bed. For a given electrode configuration (i.e., electrode length \(L\), electrode angle \(\theta\) and electrode distance \(d_0\)), the corresponding value of the critical high-voltage \(U_{\min}\) can be computed from (12):

\[
U_{\min} = \frac{(90d_0 + \pi \theta L portals)}{[G \times \cos(\theta) / \mu_{\max} - G \times \sin(\theta) - F_i]}(180Q)
\]

(13)

For example, in the case of a granule characterized by \(r = 1\) mm, \(\rho = 1050\) kg m\(^{-3}\) and \(Q = 330\) pC, if \(L = 0.5\) m, \(\theta = 10^\circ\) and \(d_0 = 0.15\) m, then \(U_{\min} = 20.535\) kV. This means that if the voltage applied to the electrode system were lower than \(\pm 20.535\) kV, the respective granule would not be collected.

The position \(L_{\max}\) of the highest point on the electrode where the granule still adheres to it can be computed from (4), (5), (10) and (11):

\[
L_{\max} = \left[ \frac{180UQ}{G \times \cos(\theta) / \mu_{\max} - G \times \sin(\theta) - F_i} - 90d_0 \right]/(\pi \theta)
\]

(14)

If the critical climbing distance \(L_{\max} > L_{\text{belt}}\), the granule passes the top of the belt electrode and the separation is successful. With \(Q, G\) and \(F_i\) constant in (14), the adhesion of the granules to the electrode can be improved by adjusting the high-voltage \(U\), the inter-electrode distance \(d_0\), the angle \(\theta\), and the coefficient of static friction \(\mu_{\max}\).

The charge/mass ratio \(Q/m\) that ensures a virtual climbing distance \(L_{\max}\) for a granule \(r = 1\) mm, \(\rho = 1050\) kg m\(^{-3}\) has been calculated for different values of the angle \(\theta\) (figure 6). The longer is the distance \(L_{\max}\), the higher should be the charge/mass ratio \(Q/m\) and the attainable charge/mass ratio significantly increases. As shown in figure 6, the \(L_{\max}\) is very sensitive to the value \(Q/m\). For example, in the case of the large angle \(\theta = 20^\circ\), the \(L_{\max}\) reduces by 50\%, from 0.4 m to 0.2 m, at a tiny diminution of \(Q/m\) from 25 nC g\(^{-1}\) to 23 nC g\(^{-1}\).

The figure 7 shows the relationship between the climbing distance \(L_{\max}\) and the charge/mass ratio \(Q/m\) for a granule \(r = 1\) mm, \(\rho = 1050\) kg m\(^{-3}\), at the different applied high voltages \(U\). The granule requires
lower charge (26.2 nC g\(^{-1}\)) at higher voltage \((U = \pm 19 \text{ kV})\) for climbing to the same distance \(L_{\text{max}} = 0.4 \text{ m}\). Setting the voltage at higher values is better. However, it should be noted that the effect of a change in the charge/mass ratio is more important than the applied voltage. The climbing distance \(L_{\text{max}}\) is more sensitive to the changes in \(Q/m\) than in \(U\). In the development of a new industrial application, the choice to make is between a more expensive high-voltage generator, capable to provide higher \(U\), or a longer residence time of the granules in the fluidized bed, so that they acquire a larger charge \(Q\), to compensate for the lower \(E\) in the formula of the Coulomb force (8).

**Figure 6.** Computed critical climbing distance \(L_{\text{max}}\) as the function of the charge/mass ratio \(Q/m\), for a granule \(r = 1 \text{ mm}\) and \(\rho = 1050 \text{ kg m}^{-3}\), at \(U = \pm 15 \text{ kV}\), \(d_0 = 15 \text{ cm}\), \(\mu_{\text{max}} = 0.2\), and different electrode angles \(\theta\).

**Figure 7.** Computed critical climbing distance \(L_{\text{max}}\) as the function of the charge/mass ratio \(Q/m\), for a granule \(r = 1 \text{ mm}\) and \(\rho = 1050 \text{ kg m}^{-3}\), at \(\theta = 10^\circ\); \(d_0 = 15 \text{ cm}\), \(\mu_{\text{max}} = 0.2\), and
different high-voltages $U$.

![Figure 8](image)

**Figure 8.** Computed critical climbing distance $L_{\text{max}}$ as function of the surface charge density $Q/S$, for granules of $\rho = 1050 \text{ kg m}^{-3}$ and various radius $r$, at $U = \pm 15 \text{ kV}$; $\theta = 10^\circ$; $d_0 = 15 \text{ cm}$, $\mu_{\text{max}} = 0.2$.

At the end of the tribo-charging process, the charge $Q$ is uniformly distributed on the surface $S$ of the granules. The relationship between the critical surface charge density $(Q/S)$ and climbing distance $L_{\text{max}}$ for granules of different sizes $r$ was computed from (14) and represented in figure 8. The larger granules ($r = 2.0 \text{ mm}$) need significantly higher surface charges densities than the smaller ones ($r = 1.0 \text{ mm}$), for the same climbing distance $L_{\text{max}}$. That means that coarser particles are much more difficult to be separated.

3. **Experimental study**

3.1. **Materials and method**

In order to validate the conclusions of the physical modeling reported in the previous section of the paper, several experiments were carried out on a granular mixture consisting of 50% Acrylonitrile Butadiene Styrene (ABS) and 50% High Impact Polystyrene (HIPS) originating from the recycling of waste electric and electronic equipment (figure 9). The particle size ranged between 2.5 and 4 mm.

The three electrode settings employed for this experimental study are described in table 1 and displayed in figures 1, 10 and 11.

| Setting | Designation | Descriptions |
|---------|-------------|--------------|
| I       | Standard    | Standard setting (figure 1). |
| II      | Additional grounded electrode | A “V” type ground electrode was placed parallel to the surface of metal belt electrodes to increase the electrostatic field strength $E$ (figure 10). |
| III     | Insulator   | The surface of the metal belt is covered by an insulating layer to limit |
layer charge leakage to the ground and change the coefficient of static friction \( \mu \) (figure 11).

**Figure 9.** Aspect of HIPS and ABS granules originating from WEEE.

**Figure 10.** Electrode setting II, V-shaped grounded electrode placed at equal distances from the two metal belt electrodes.

At first, 2 kg of a (50% ABS +50% HIPS) granular mixture were fed into the separation chamber to be charged for 4 min at the maximum air flow. Then the high voltage was applied to the electrodes and the belt speed was set at 16 cm/sec. to collect the products. Finally, the mass of products in the collector were measured at 4 min, 10 min and 15 min after high-voltage switch-on. After 15 minutes, there were no more products to be collected.
3.2. Results and discussion

The recovery $R_A$ of product $A$ was computed with:

$$ R_A = \left( \frac{m_A}{m_{A_{\text{total}}}} \right) \times 100\% $$  \hspace{1cm} (15) 

$m_A$ is the mass of the $A$ granules accumulated in the collector, and $m_{A_{\text{total}}}$ is the total mass of $A$ in the feed. The separation results are given in table 2, figure 12 and figure 13. In all cases, ABS granules separate better than HIPS, as the granule-to-wall collisions increase the total charge of the former, but have an adverse effect on the latter. Both the ground electrode (II) and the insulator layer (III) settings increased the recovery of ABS granules (figure 12). For this kind of granules, the setting III leads to better results than the setting II. In the case of HIPS granules (figure 13) the best results were obtained for the setting II. Surprisingly, the results obtained with the setting III were worse than with the standard setting (I).

Table 2. Cumulated recoveries of ABS and HIPS at 4, 10, and 15 min after high-voltage switch-on, using different electrode settings.

| Settings          | I Standard | II Ground electrode | III Insulator layer |
|-------------------|------------|---------------------|---------------------|
|                   | ABS(%)     | HIPS(%)             | ABS(%)             | HIPS(%)             | ABS(%)     | HIPS(%)             |
| Time points       |            |                     |                     |                     |            |                     |
| 4 min             | 29.26      | 12.84               | 32.65               | 30.42               | 30.3       | 10.95               |
| 10 min            | 39.76      | 16.14               | 43.65               | 38.92               | 49.95      | 14.42               |
| 15 min            | 46.76      | 18.14               | 48.15               | 42.4                | 57.83      | 15.87               |

Figure 11. Electrode setting III, metal belt electrodes covered with an insulator layer.
Figure 12. ABS recovery as function of time, for three different electrode settings (I: standard setting; II: additional grounded electrode setting; III: insulator layer setting).

Figure 13. HIPS recovery as function of time, for three different electrode settings (I: standard setting; II: additional grounded electrode setting; III: insulator layer setting).

These experimental findings can be discussed in the light of the physical model established in the previous section. Thus, the setting II increased the intensity $E$ of the electric field at the surface of the electrodes. Granules with lower charge $Q$ satisfy (9), adhere to the electrodes, and are collected as distinct products. The recoveries are improved. However, the effect of setting II on ABS is not as spectacular as on HIPS (figures 12 and 13). The ABS granules being better charged than HIPS, they will benefit less of the increase in the intensity of the electric field: in their case, the virtual climbing distance already satisfies the condition $L_{\text{max}} > L_{\text{top}}$. 
The insulating layer in setting III increased the static friction coefficient $\mu_{\text{max}}$ of both types of granules and was expected to improve the separation, due to the increase of $L_{\text{max}}$ given by (14). No such effect was obtained in the case of HIPS granules, as in their case it was surpassed by the decrease of the electric image force $F_i$. Indeed, the expression of $F_i$ is no longer the one given by (7), as it should take into account the thickness $a$ of the insulating layer:

$$F_i = Q^2 / \left[ 4 \pi \epsilon \left( 2(r + a) \right)^3 \right]$$

According to (16), the presence of the layer diminishes $F_i$ and hence the virtual climbing distance $L_{\text{max}}$.

A third physical mechanism should be taken into account in order to explain the experimental observations in figures 12 and 13: the decay of the charge carried by the granules. In the standard setting, where the granules are in direct contact to the electrode, the charge of ABS granules decays faster than that of HIPS. The insulating layer in setting III limits the charge leakage. In this way, the charge of ABS remains practically constant and equal to the initial value. The increase of $Q$ as compared to its value in setting I is accompanied by an increase of $L_{\text{max}}$ in (14), which explains the better separation results. HIPS particle benefit less of this slow down of the charge decay and their behavior is more affected by the decrease of the electric image force $F_i$, as discussed above. The insulating layer has an opposite effects on the collection of ABS and HIPS granules, positive for the former and negative for the latter.

4. Conclusions

The physical model of granule adhesion on the belt-electrodes of a tribo-aero-electrostatic separator enables the definition of two critical parameters for the design of such equipment: the minimum electric field strength and the maximum electrode length for which a charged granule can be safely collected. Both parameters depend on the charge of the granules and the geometry of the electrode system. By increasing the angle between the belt electrodes and the vertical plane, the minimum electric field strength diminishes.

By placing a V-shaped grounded electrode equally-distanced from the two high-voltage electrodes, it is possible to improve the outcome of the electrostatic separation, as it increases the electric field strength and hence the electric forces that make the particles adhere to the metallic belts and be transferred to the collecting boxes. Particle adhesion can also be enhanced by covering the belt electrodes with an insulating layer that would reduce the charge leakage and increase the friction coefficient. The effect of the insulating layer is more important in the case of the insulating materials that are characterized by relatively-fast charge decay, such as ABS.

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References

[1] Boland D and Geldart D 1971/1972 Powder Technol. 5 289
[2] Dwari R K and Rao K H 2009 Minerals Eng. 22 119
[3] Rokkam R G, Fox R O and Muhle M E 2010 Powder Technol. 203 109
[4] Calin L, Mihalciou A, Iuga A and Dascalescu L 2007 Part. Sci. & Technol. 25 205
[5] Calin L, Caliap L, Neamtu V, Morar R, Iuga A, Samuila A and Dascalescu L 2008 IEEE Trans. Ind. Appl. 44 1045
[6] Miloudi M, Medles K, Tilmatine A, Brahami M and Dascalescu L 2011 J. Electrostat. 69 631
[7] Calin L and Dascalescu L 2010 Patent FR2943561, WO2010109096
[8] Miloudi M, Remadnia M, Dragan C, Medles K, Tilmatine A and Dascalescu L 2011 Conf. Rec. IEEE IAS Ann. Meet. (Orlando, FL, USA) DOI: 10.1109/IAS.2011.6074274
[9] Ciborowski J S and Wlodarski A 1962 Chem. Eng. Sci. 17 23–32
[10] Guardiola J, Rojo V and Ramos G 1996 J. Electrostat. 37 1
[11] Ali F S, Inculet I I and Tedoldi A 1999 J. Electrostat. 45 199
[12] Frigon N L and Mathews D 1996 Practical Guide to Experimental Design (New York: Wiley)
[13] Eriksson L, Johansson E, Kettaneh-Wold N, Wikström C and Wold S 2000 Design of Experiments. Principles and Applications (Stockholm: Learnways AB)
[14] Dragan C, Fati O, Radu M, Calin L, Samuila A and Dascalescu L 2011 IEEE Trans. Ind. Appl. 47 1922
[15] Bilici M, Dascalescu L, Dragan C, Fati O, Iuga A and Samuila A 2011 IEEE Trans. DEI 18 1476
[16] Rahou F Z, Tilmatine A, Bilici M and Dascalescu L 2012 IEEE Trans. Ind. Appl. 48 816