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Hakim Moulai, Thami Zegloul, Nour-Eddine Menad, Lucian Dascalescu. Effect of high voltage and electrode configuration on the trajectories of metallic particles in roll-type electrostatic separators for granular mixtures. *Journal of Electrostatics*, 2025, 133, pp.104014. <10.1016/j.elstat.2024.104014>. <hal-04893607>

HAL Id: hal-04893607

<https://hal.science/hal-04893607v1>

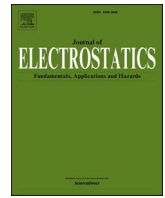
Submitted on 21 Jan 2025

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Effect of high voltage and electrode configuration on the trajectories of metallic particles in roll-type electrostatic separators for granular mixtures

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ARTICLE INFO

Keywords:

Electrostatic separation
Mm-sized conductive particles
Visualization of particles trajectory
Roll-type electrostatic separator
Electric field
Electric forces

ABSTRACT

Electrostatic separation is a technique that uses electric field forces exerted on charged or polarized bodies for sorting the constituents of granular mixtures in various domains: minerals beneficiation, food processing, waste recycling, etc. In the case of the specific electrostatic separator that is the subject of this study, the electric field is generated between a rotating-roll electrode, connected to the ground, and a static electrode with inverted S profile connected to a high voltage (HV) supply. This paper is aimed at evaluating the effect of two factors: the high voltage applied between the two electrodes and the distance between them. A high-speed video camera was used to record the trajectories of mm-sized aluminum and copper particles. The visualization of these trajectories provided a better understanding of the dynamics of particles movement in the electric field of the separator. It enabled to adjust the applied high voltage and the inter-electrode distance to avoid the impacts between the fine aluminum particles and the static electrode, while driving the two types of metallic particles into different collecting compartments. The conclusions of the study will be implemented on a pilot-plant roll-type electrostatic separator integrated to the production line of an industrial recycler.

1. Introduction

Waste electrical and electronic equipment (WEEE) are rich in heavy metals (mercury, zinc, chromium, cadmium, lead, etc.) and halogens (bromine, chlorine, etc.) as well as precious metals (Ag, Pd, Au, etc.). Some of these materials represent a danger to the environment and human health due to their persistent toxic nature [1,2]. Their stable supply is crucial for the transition to a sustainable and circular economy. The characterization, treatment and recovery of the materials contained in this waste stream are of great environmental and economic importance, which justifies the research efforts for developing effective recycling processes.

The electrostatic separation technique used in mineral processing is likely to be a solution for extracting the metallic particles present in finely-ground WEEE. This technique is based on two physical mechanisms for imparting electric charges to particles of millimeter and sub-millimeter sizes: corona discharge and electrostatic induction. In a roll-type electrostatic separator, which is the most widely used in industry, the sorting of differently charged particles is achieved by the Coulomb forces which attract on them in the intense electric field created between a static electrode connected to high voltage and a

rotating roll electrode connected to the ground [3]. Other electrostatic separation devices have been successfully developed, particularly when it consists of separating fine insulating particles of different types [4–7].

To broaden the range of particles to be recovered and improve the separation performance, different types of electrodes [8–10] or even two rotating cylindrical electrodes arranged in cascade [11,12] have been proposed to equip the electrostatic separators. The trajectories of the particles in these separators are the result of the combined action of three major forces: Coulomb force, gravitational force and centrifugal force [13–18].

The air drag force is usually neglected, as it is particularly influential only when separating particles of very small dimensions (sub-millimeter). The electric image force should be considered in the study of separation processes involving insulating particles [3].

The most relevant influencing parameters on the quality of the separation are the splitter position [9,19], the roll speed [9,19,20], the applied voltage [15,21,22] as well as the relative position of the electrodes [19,20,22].

The electrostatic separators employed for WEEE recycling must process particles of different sizes and shapes, depending on the materials involved. Copper and aluminum represent, besides steel, the major

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<https://doi.org/10.1016/j.elstat.2024.104014>

Received 6 November 2024; Received in revised form 10 December 2024; Accepted 19 December 2024

Available online 25 December 2024

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metals in WEEE [23–25]. The size distribution of Cu particles is mainly below 1 mm, those of Al are above 2 mm [23], while the largest dimension of photo-voltaic panels particles is less than 0.5 mm [20]. The wide distribution of particle sizes represents a major difficulty for their appropriate electrostatic processing. There are already calls for standardization of particle sizes to optimize the separation processes [26].

Visualizing the trajectory of particles using a high-speed camera has already been used to evaluate the influence of electrode configuration on the efficiency of an electrostatic separator [10,27]. The aim of the present work is triple:

- (i) demonstrate the effectiveness of the electrostatic drum separator as a sorting tool of copper/aluminum granular mixtures from WEEE;
- (ii) deepen the study of the effects of two factors that should be controlled for optimizing the separation process: the high voltage applied between the electrodes and the distance between them;
- (iii) prepare the conditions for implementing a pilot electrostatic separator integrated into the production line of an industrial WEEE recycler.

2. Materials and method

The aluminum and copper particles studied in this work (diameter from 0.5 mm to 1 mm; length <10 mm) were picked up from a fraction obtained after a series of operations specific to the processing of WEEE at Environment Recycling Company, France: manual depollution, crushing, shredding, electromagnetic separation, optical sorting and classifying (Fig. 1).

A roll-type electrostatic separator (Carpco Inc, Jacksonville, FL) was used for this study (Figs. 2 and 3).

The analysis of the electric field distribution between the inverted S-shaped static electrode connected to a HV supply and the rotating roll electrode connected to the ground point out the presence of four distinct zones (Fig. 4):

Zone 1, where the particles lift off the surface of the rotating roll under the double effect of the centrifuge force F_c and Coulomb force F_e generated by the relatively high electric field at the upper edge of the static electrode.

Zone 2, characterized by a local intensification of the electric field, which will increase the effect of the Coulomb force that attracts the particle to the static electrode.

Zone 3, where the intensity of the electric field progressively decreases, and the effect of the Coulomb force decreases.

Zone 4, characterized by an almost null electric field, so that the particle is only submitted to the gravitational force.



Fig. 1. Cu and Al particles picked up from the WEEE processing at Environmental Recycling Company, France.

For the relatively heavy particles of millimetric dimensions considered in this study and moving in air of relatively low velocity, the drag force can be neglected with regard to the electrical, gravitational and centrifugal forces.

The first series of experiments were carried out with a group of three aluminum particles and then with a group of three copper particles of different sizes (diameter from 0.5 mm to 1 mm; length <10 mm). Based on the results of preliminary experiments, the operating conditions were established as follows: diameter of rotating cylindrical roll electrode: $D = 36$ cm, distance between the rotating roll electrode and the edge of the static electrode: $d_1 = 6$ cm, distance between the rotating roll electrode and the static electrode: $d_2 = 4$ cm, angular position of the upper edge of the electrode: $\alpha_1 = 10^\circ$, angular position of the static electrode support: $\alpha_2 = 45^\circ$, rotation speed of the roll electrode: $n = 70$ rpm, frequency of the vibratory feeder: $f = 100$ Hz. The applied high voltage was varied from $U = -13$ kV to $U = -21$ kV with a step of -4 kV. The voltage was not increased over -21 kV to avoid the collisions between the small particles and the static electrode.

The experiments were conducted at constant ambient conditions: temperature: $T = 19^\circ\text{C} \pm 1^\circ\text{C}$ and relative humidity: $RH = 71\% \pm 1.5\%$, which had no influence on the purely electrostatic induction charging of the metallic particles that made the object of the study.

The two same groups of aluminum and copper particles were used in the second series of experiments carried out by varying the distance d_2 between the inverted S-shaped static electrode and the rotating roll electrode. The goal was to find a position that was close enough to the rotating roll electrode to generate an intense electric field but avoiding collisions of the particles with the HV electrode. Therefore, the HV static electrode was brought closer to the rotating roll electrode from $d_2 = 5$ cm to $d_2 = 3$ cm, with a 1 cm step. This distance was not increased over $d_2 = 5$ cm because the electric field becomes too weak to attract and separate the particles. Likewise, the distance was not less than 3 cm to avoid electric arcs triggering between the electrodes, a phenomenon that would influence the particles trajectories.

For this series of experiments, a DC voltage $U = -17$ kV was applied on the inverted S-shaped electrode, the upper edge of which was varied from $d_1 = 7$ cm to $d_1 = 5$ cm to be correlated with the values of d_2 . The other operating conditions were as for the first series of experiments: $D = 36$ cm; $n = 70$ rpm; $\alpha_1 = 10^\circ$; $\alpha_2 = 45^\circ$; $f = 100$ Hz. The relative humidity of the ambient air was $RH = 58\% \pm 1\%$ and the temperature $T = 16^\circ\text{C} \pm 1^\circ\text{C}$.

Finally, an electrostatic separation experiment was carried out with a set composed of two copper particles and two aluminum particles, like the ones described before. The operating parameters for this experiment were fixed as follows: $D = 36$ cm; $d_1 = 5$ cm; $d_2 = 3$ cm; $\alpha_1 = 10^\circ$; $\alpha_2 = 45^\circ$; $U = -17$ kV; $n = 70$ rpm; $f = 100$ Hz. The ambient conditions were $RH = 45\% \pm 1.5\%$ and $T = 17^\circ\text{C} \pm 1.5^\circ\text{C}$. Particle trajectories were visualized by using a high-speed Phantom VEO 340 L video camera controlled by Dynamics Studio 6.6 software (Fig. 3). After several preliminary tests, the parameters of the camera were fixed as follows: number of images: 160; frequency: 200 Hz; time interval between images: 5 ms; image size: 2560×1600 pixels; ray depth: 12 bits/pixel; exposure time: $100 \mu\text{s}$ and pulse width: $90 \mu\text{s}$.

3. Results and discussions

Visualization of particles trajectories during electrostatic induction separation experiments has enabled us to assess the effects of high voltage and inter-electrode distance on aluminum and copper particles trajectories, and to determine the zones where each metal is recovered. The choice of particle size was made after a series of preliminary experiments. Indeed, with particles of sizes beyond a certain threshold (1 mm in diameter, 10 mm in length) the gravitational forces surpass the Coulomb forces that are no longer able to drive them to the static electrode. Nevertheless, particles of 10 mm in length are very rare in actual mixtures to be separated. In the case of very fine particles (smaller

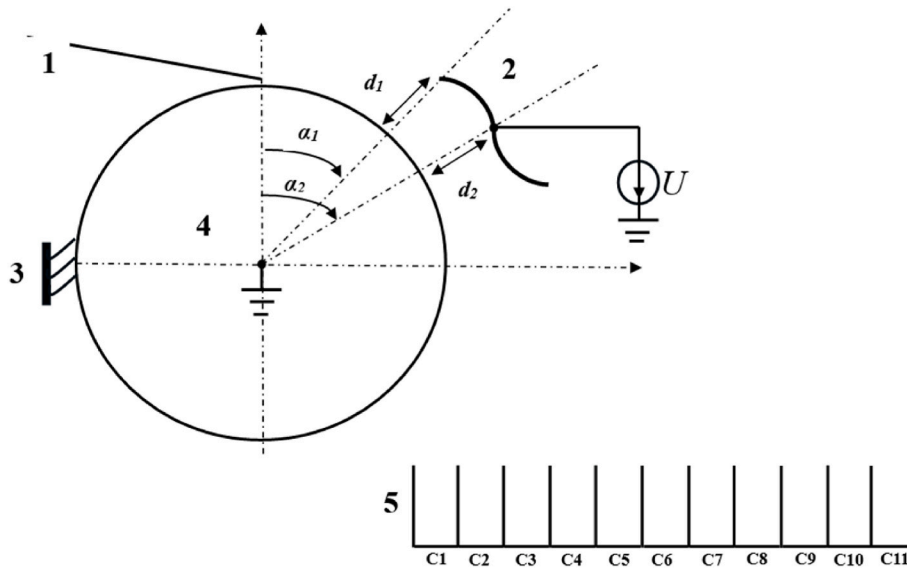


Fig. 2. Schematic diagram of the roll-type electrostatic separator: (1) vibratory feeder, (2) inverted S-shaped static electrode connected to the high-voltage supply U , (3) brush, (4) rotating roll electrode connected to the ground, (5) collecting compartments.

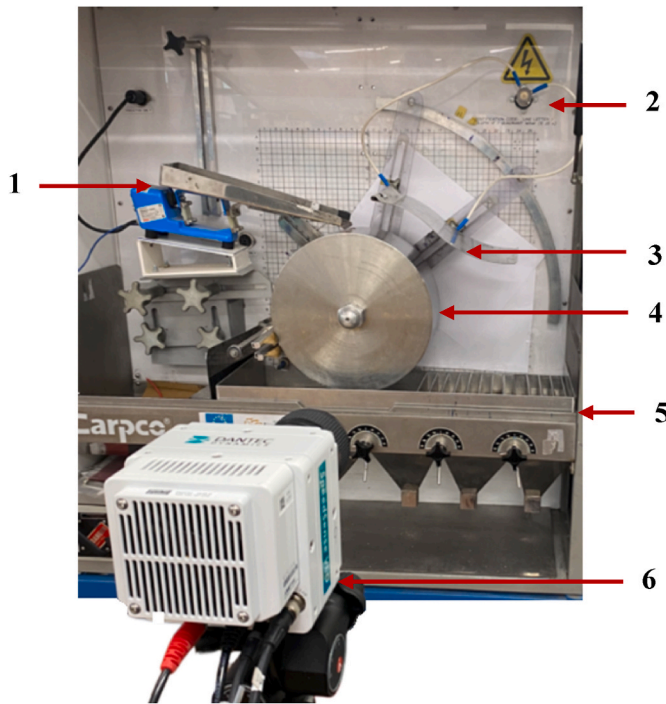


Fig. 3. Photo showing the position of the high-speed video camera facing the roll-type electrostatic separator: (1) vibratory feeder, (2) high voltage connector, (3) inverted S-shaped static electrode connected to the high-voltage supply, (4) rotating roll electrode connected to the ground, (5) collecting compartments, (6) Phantom VEO 340 L high-speed video camera.

than 0.5 mm), preliminary tests were also carried out by varying the speed of the rotating roll electrode and the position of the static electrode to provide an appropriate centrifugal force and a sufficient electric field without excessively increasing the applied voltage.

3.1. Influence of the applied high voltage on aluminum particles trajectory

Fig. 5 shows the trajectories of the aluminum particles recorded as a function of the applied voltage. The best particle attraction without

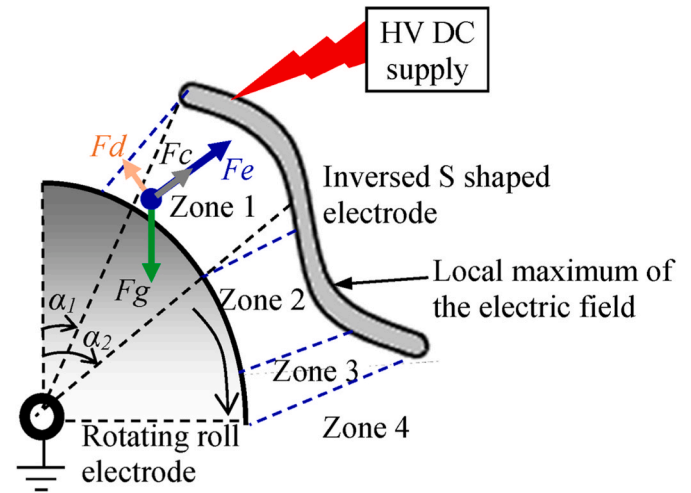


Fig. 4. Zones of electric field influence on the trajectory of metallic particles between the inverted S-shaped static electrode and the rotating roll electrode; F_e : electric field force (Coulomb force); F_c : centrifugal force; F_g : gravitational force; F_d : air drag force.

impact with the static electrode was obtained at a voltage of 17 kV (negative polarity). Indeed, by increasing the voltage (in absolute value) from 13 kV to 17 kV, the electric field becomes more intense, the particles get better charged and are subjected to stronger Coulomb forces that drive them towards the static electrode. The separation of the particles observed in this figure could be explained by their mass differences where the particle of lower mass is subject to less gravitational force. As a result, the acceleration of lighter particles is greater, leading them to be attracted more strongly towards the high-voltage electrode and to settle in the right-hand area of the collector. By increasing the voltage to 21 kV, the effect of electric forces overpasses that of the gravitational forces, and the smaller particles are strongly attracted to the static electrode, collide with it and their trajectories do no longer end in the appropriate collecting compartment. A similar result was reported in Ref. [10]. These impacts with the static electrode should be avoided for better trajectory control. Particle movement between detachment from the rotating cylindrical electrode and landing in the appropriate compartment takes place via different mechanisms, depending on the

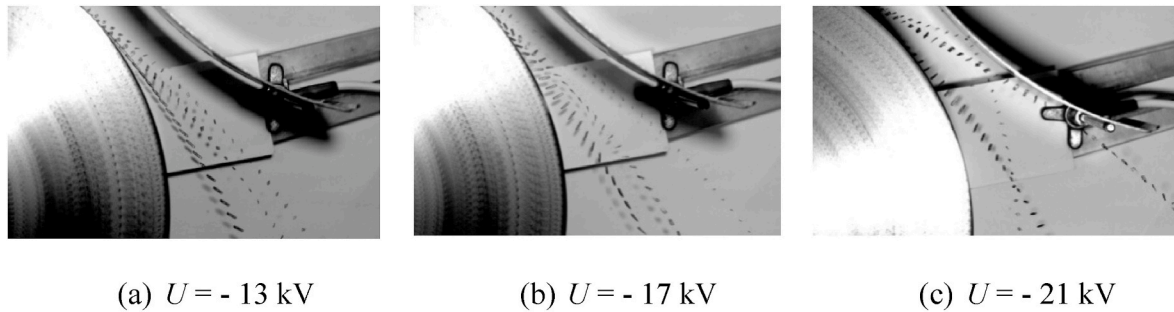


Fig. 5. High-speed camera recordings of aluminum particles trajectory as a function of the applied voltage U , for $d_1 = 6$ cm, $d_2 = 4$ cm, $\alpha_1 = 10^\circ$, $\alpha_2 = 45^\circ$, $n = 70$ rpm and $f = 100$ Hz.

ratio of the forces involved, particularly when the particles are cylindrical in shape. At lower electric field strengths, the particles tend to plunge at a slight angle towards the high-field zone. At higher electric fields, above 13 kV, the particles are drawn towards the static electrode with the tip oriented perpendicular to its surface. The particles seem to rotate around themselves when sufficiently light as they pass through the strong-field zone corresponding to the second curvature of the inverse S-shaped electrode.

3.2. Influence of the inter-electrode distance on aluminum particles trajectory

The particles trajectory recorded for three pairs of inter-electrode distances d_1 and d_2 are shown on Fig. 6. As expected, the smallest particle was attracted more than the others by the electrical force towards the static electrode. The decrease in inter-electrode distances d_1 and d_2 was accompanied by a greater deflection of the particles towards the static electrode, due to the increase of particle charge and the intensification of the electric field in the active zone of the separator. Indeed, the higher these two latter parameters are, the stronger the electrical force governing the trajectory of the particle will be.

3.3. Influence of the inter-electrode distance and applied voltage on copper particles trajectory

Fig. 7 shows that, despite the use of the same operation conditions as for the aluminum particles, small differences could be noted between the trajectories of the three copper particles of different sizes. Since the gravitational force depends on particle mass, and that copper particles have a relatively high mass density, their trajectories are more governed by this force, which surpasses the electrical force.

3.4. Separation of copper and aluminum particles

The separation trajectories of copper and aluminum particles are



Fig. 7. High-speed camera recordings of the trajectory of copper particles for $U = -17$ kV, $d_1 = 7$ cm, $d_2 = 4$ cm, $\alpha_1 = 10^\circ$, $\alpha_2 = 45^\circ$, $n = 70$ rpm and $f = 100$ Hz.

shown on Fig. 8. These particles follow different trajectories, in spite of the fact that the electrostatic charge acquired by electrostatic induction is similar for copper and aluminum particles that have similar sizes. The electrostatic forces have the same order of magnitude for the two classes of particles, but they have a stronger effect on the aluminum particles, which have a lower mass (density). As a result, the gravitational forces prevail on the electrical forces in the case of copper particles, which will be less deviated in the electric field and be collected in the left compartment A. The lighter aluminum particles will be strongly deviated to the static electrode and land in the right compartment B. Thus, the copper and aluminum particles can be successfully separated.

Based on the results presented above, 4 modes of particle trajectory dynamics have been identified, depending on the predominance of electrical, centrifugal and gravitational forces:

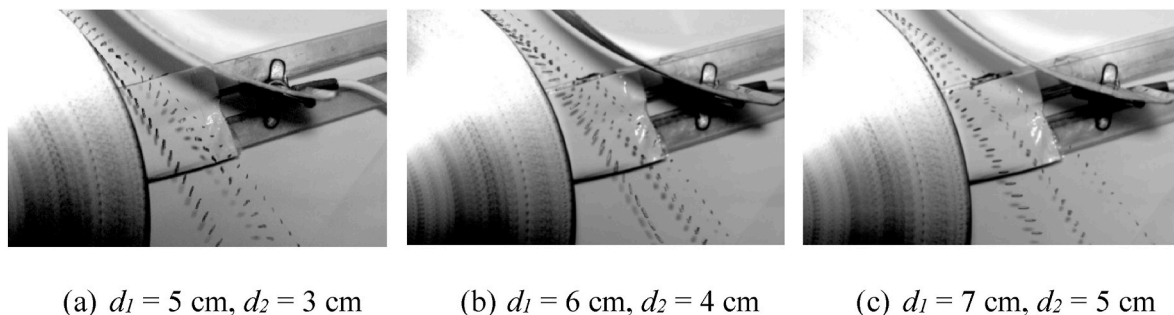


Fig. 6. Fast camera recording of aluminum particles trajectory as a function of the inter-electrode distance d_2 , for $U = -17$ kV, $\alpha_1 = 10^\circ$, $\alpha_2 = 45^\circ$, $n = 70$ rpm and $f = 100$ Hz.

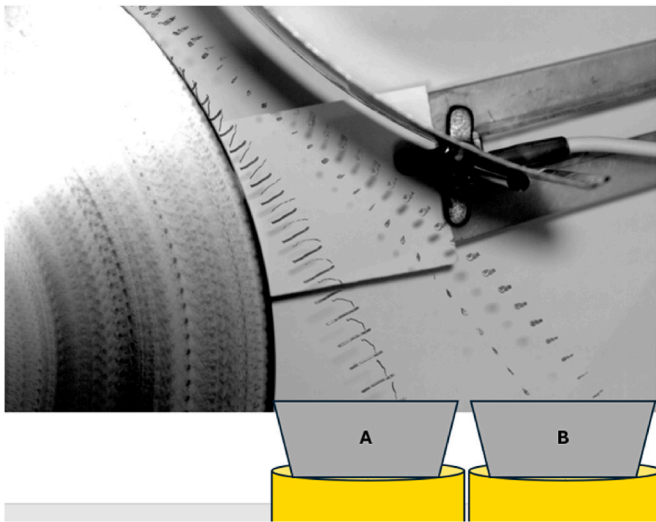


Fig. 8. High-speed camera recordings of the trajectory of copper and aluminum particles; $d_1 = 5$ cm; $d_2 = 3$ cm; $\alpha_1 = 10^\circ$; $\alpha_2 = 45^\circ$; $U = -17$ kV; $n = 70$ rpm; $f = 100$ Hz.

Mode 1: The electric and centrifugal forces are too small compared to the gravitational force. As a result, the trajectory of the particle is less affected by the electric field and centrifugal force; it remains close to the rotating roll electrode. The particle lands into the left compartment.

Mode 2: The electrical forces dominate the gravitational forces. In the zone 1 defined on Fig. 4, while in contact with the grounded roll electrode, the particle gets positively charged by electrostatic induction. It detaches from the surface of the electrode under the action of the centrifugal and electrical forces. When the particle enters the zone 2, it gets oriented along the electric field lines, with its tips directed towards the electrodes. As the electric field decreases in zone 3, the particle rotates around itself, under the effect of the gravitational force, and plunges into the middle compartment.

Mode 3: The electric field is even stronger than in mode 2. Under the action of the corresponding electrical forces, the particle is strongly attracted at the entrance of zone 1. In this zone, the electrical forces largely surpass the gravitational forces. Consequently, the trajectories of the smaller (and lighter) particles skim the maximum-field point of the static electrode and reach the far-right compartment after turning around more than once.

Mode 4: As effect of further increase of the electric field (by increasing the applied high-voltage or decreasing the inter-electrode distance), the smaller particles, subjected to the action of Coulomb forces, will collide the static electrode. In contact with this electrode, the particles will change the sign of their charge, will be attracted to the roll electrode and collected in the left-hand compartment.

4. Conclusions

The present work points out that controlling the trajectories of metal particles may improve the efficiency of roll-type electrostatic separators currently employed for the processing of granular WEEE.

- (1) Considering the relative similarity of the electrical conductivities of the metals, their electrostatic separation cannot be achieved without a fine adjustment of each influential factor. Nevertheless, the results reported in this paper demonstrate the effectiveness of the electrostatic drum separator as a sorting tool of copper/aluminum granular mixtures from WEEE.
- (2) High-speed video camera visualization of the trajectories of copper and aluminum particles employed in this study

(aluminum and copper wire segments, diameters 0.5 mm–1 mm, lengths <10 mm) proved to be an effective tool for evaluating the effects of these factors. This experimental technique contributed to a better understanding of the dynamics of particles movement in the electric field of the separator; it enabled the determination of the applied high voltage (-17 kV) and the distance between electrodes (4 cm) which can provide rigorously distinct trajectories for the two metals, while avoiding the collisions between light aluminum particles and the HV static electrode.

- (3) The observations reported in the paper have also pointed out the need for improving the crushing operation of the waste, to reduce the dispersion of particle sizes in the mixture subjected to electrostatic separation.
- (4) Work is in progress to implement the conclusions of the study on a pilot-plant roll-type electrostatic separator integrated to the production line of an industrial recycler of waste electrical and electronic equipment.

CRedit authorship contribution statement

Hakim Moulai: Writing – original draft, Visualization, Investigation, Data curation. **Thami Zeghloul:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Nour-eddine Menad:** Writing – review & editing, Methodology, Formal analysis. **Lucian Dascalescu:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- [1] V. Forti, C.P. Baldé, R. Kuehr, G. Bel, The Global E-Waste Monitor 2020: Quantities, Flows, and the Circular Economy Potential. Retrieved 01. <http://ewastemonitor.info/>.
- [2] N. Menad, S. Guignot, J.A. Houwelingen, New characterisation method of electrical and electronic equipment wastes (WEEE), *Waste Manag.* 33 (2013) 706–7013.
- [3] L. Dascalescu, T. Zeghloul, A. Iuga, Electrostatic separation of metals and plastics from waste electrical and electronic equipment, in: *WEEE Recycling. Research Development and Policies*, Elsevier, Amsterdam, the Netherlands, 2016, pp. 75–106.
- [4] S. Messal, T. Zeghloul, A. Mekhalef-Benhafssa, K. Medles, L. Dascalescu, Experimental study of a tribo-aero-electrostatic separator for finely grinded matter, *J. Electrostat.* 89 (2017) 59–68.
- [5] J. Li, L. Dascalescu, M. Bilici, Z. Xu, Numerical modeling of the trajectories of plastic granules in a tribo-aeroelectrostatic separator, *J. Electrostat.* 71 (2013) 281–286.
- [6] W. Aksa, K. Medles, M. Rezoug, M.F. Boukhoula, M. Bilici, L. Dascalescu, Two-stage electrostatic separator for the recycling of plastics from waste electrical and electronic equipment, *J. Electrostat.* 71 (2013) 681–688.
- [7] D.E. Fekir, M. Miloudi, I. Kimi, F. Miloua, A. Tilmatine, Experimental and numerical analysis of a new tribo-electrostatic separator with coaxial cylindrical electrodes for plastic binary granular mixtures, *J. Electrostat.* 108 (2020) 103523.
- [8] G. Richard, A. Salama, K. Medles, T. Zeghloul, L. Dascalescu, Comparative study of three high-voltage electrode configurations for the electrostatic separation of aluminum, copper and PVC from granular WEEE, *J. Electrostat.* 88 (2017) 29–34.
- [9] G. Bedekovic, R. Trbovic, Electrostatic separation of aluminum from residue of electric cables recycling process, *Waste Manag.* 108 (2020) 21–27.
- [10] A. Salama, G. Richard, K. Medles, T. Zeghloul, L. Dascalescu, Distinct recovery of copper and aluminum from waste electric wires using a roll-type electrostatic separator, *Waste Manag.* 76 (2018) 207–216.
- [11] J. Wu, J. Li, Z. Xu, Electrostatic separation for multi-size granule of crushed printed circuit board waste using two-roll separator, *J. Hazard Mater.* 159 (2008) 230–234.
- [12] W. Jiang, L. Jia, X. Zhen-ming, A new two-roll electrostatic separator for recycling of metals and nonmetals from waste printed circuit board, *J. Hazard Mater.* 161 (2009) 257–262.

- [13] K.B. Tennal, D. Lindquist, M.K. Mazumder, R. Rajan, W. Guo, Efficiency of electrostatic separation of minerals from coal as function of size and charge distributions of coal particles, *IEEE Trans. Ind. Appl.* 4 (1999) 2137–2142.
- [14] L. Dascalescu, Mouvements des particules conductrices dans un séparateur à haute tension pour matériaux granulaires, *J. Electrostat.* 32 (1994) 305–316.
- [15] J. Wu, J. Li, Z. Xu, An improved model for computing the trajectories of conductive particles in roll-type electrostatic separator for recycling metals from WEEE, *J. Hazard Mater.* 167 (2009) 489–493.
- [16] M. Younes, A. Tilmatine, K. Medles, M. Rahli, L. Dascalescu, Numerical modeling of conductive particle trajectories in roll-type electrostatic separators, *IAS Annu. Meet, IEEE Ind. Appl. Soc.* 4 (2005) 2601–2606.
- [17] L. Dascalescu, A. Mizuno, R. Tobazeon, P. Atten, R. Morar, A. Iuga, M. Mihaiulescu, A. Samuila, Charges and forces on conductive particles in roll-type corona electrostatic separators, *IEEE Trans. Ind. Appl.* 31 (1995) 947–956.
- [18] L. Dascalescu, R. Tobazeon, P. Atten, Behaviour of conducting particles in corona dominated electric fields, *J. Phys. D Appl. Phys.* 28 (1995) 1611–1618.
- [19] A.V.M. Silveira, M.P. Santana, E.H. Tanabe, D.A. Bertuol, Recovery of valuable materials from spent lithium ion batteries using electrostatic separation, *Int. J. Miner. Process.* 169 (2017) 91–98.
- [20] R.A. de Souza, H.M. Veit, Study of electrostatic separation to concentrate silver, aluminum, and silicon from solar panel scraps, *Circular Ec* 2 (2023) 100027.
- [21] W. Jiang, L. Jia, X. Zhen-ming, Optimization of key factors of the electrostatic separation for crushed PCB wastes using roll-type separator, *J. Hazard Mater.* 154 (2008) 161–167.
- [22] F. Hamerski, A. Kruppenauer, A.M. Bernardes, H.M. Veit, Improved settings of a corona-electrostatic separator for copper concentration from waste printed circuit boards, *J. Environ. Chem. Eng.* 7 (2019) 102896.
- [23] A. Marra, A. Cesaro, V. Belgiorno, Separation efficiency of valuable and critical metals in WEEE mechanical treatments, *J. Clean. Prod.* 186 (2018) 490–498.
- [24] L.H. Yamane, V.T. de Moraes, D.C.R. Espinosa, J.A.S. Tenório, Recycling of WEEE: characterization of spent printed circuit boards from mobile phones and computers, *Waste Manag.* 31 (2011) 2553–2558.
- [25] L. Zhang, Z. Xu, A review of current progress of recycling technologies for metals from waste electrical and electronic equipment, *J. Clean. Prod.* 127 (2016) 19–36.
- [26] F. Maisela, P. Chancerela, G. Dimitrovab, J. Emmericha, N.F. Nissenb, M. Schneider-Ramelowa, Preparing WEEE plastics for recycling – how optimal particle sizes in preprocessing can improve the separation efficiency of high-quality plastics, *Resour. Conserv. Recycl.* 154 (2020) 104619.
- [27] M. Maammar, T. Zegloul, W. Aksa, S. Touhami, I. Achouri, L. Dascalescu, Factors that influence the trajectories of charged insulating particles in roll-type electrostatic separators, *J. Electrostat.* 115 (2022) 103672.