Concept and Design of the Test Bench for Electrostatic Separation in Plastic Recycling Application

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Abstract. Plastics recycling has become a key industry in developed countries, to reduce ecological damage and save non-renewable resources. This paper discusses the concept and the design of electrostatic separator as a test bench for the separation of different plastics in recycling applications. In the automotive recycling process, all these waste materials must be processed further for re-entering the cycle or thermal utilization. The following application presents the possibility of research and technological tests by changing several parameters, such as a position of the electrodes, control of the polarity and voltage, variable speed of feeder and drum, and also tribo-electrification parameters (time, intensity). The impact of process parameters on the efficiency of the plastic separation can be analyzed by the developed a specialized computer vision system. The preliminary results of conducted tests showed that separation is dependent on many variations of parameters. The results of this study indicate that the proposed innovative design of the research stand ensures the high research potential of the proposed equipment.

1 Introduction

Nowadays, for ecological, economic and legal reasons, there is an increase in interest in the plastics recycling, especially in the automotive sector [1–4]. The applying of plastics in the car manufacturing industry presents some advantages, such as car mass reduction, which leads to lower fuel consumption and a decrease in emissions of Green House Gasses (GHG). In the European Parliament Directive 2000/53/EC of 18 September 2000 established rules for dealing with end-of-life vehicles (ELVs), including the indicated levels of recovery [5]. For example, in the 2017 year in the EU about 88 % of parts and materials were reused and recycled [6]. The provisions execute producer responsibility in the field of material recycling processes and support the development of the market of recycled materials in the direction of the circular economy [3]. It is assumed that by 2025 the share of recycled plastics in new cars will amount to 25%, and by 2030 - 30% [4]. Hence, it is important to work on the improvement and development of new technologies for recycling polymers waste [1, 2, 4, 7, 8]. From a production point of view, this waste should be treated as a valuable secondary material that can be recycled into the production of car parts (bumper, airbag, carpeting, radiator grills, headlight, etc.).

The basic activities in the preparation of polymer waste for recycling include processes of segregation and separation. In the case of cars, the problem is mainly the presence of a large variety of plastics that require separation [9]. Main plastic materials used in cars include polypropylene (PP), polyurethane (PU), polyamide (PA), polycarbonate (PC), polyvinylchloride (PVC), polyformaldehyde (POM), acrylonitrile–butadiene–styrene (ABS), poly(methyl methacrylate)–PMMA), thermoset composites, thermoplastic polyester poly(butylene terephthalate)– (PBT) and poly(ethylene terephthalate)– (PET)[10]. In the form of mixed form they are often immiscible blends, preventing further plastics processing, therefore it is necessary to perform their separation into different fractions material.

The process of sorting plastics consists in separating the multicomponent system (mixture) into fractions that differ in physical properties, i.e. geometric particle size, density (cyclone separator, sink-flotation), magnetic (magnetic separator) and electrical properties (electrostatic separator), wettability [4, 11, 12]. One of the problematic processes of modern waste management is the economically and technologically ineffective separation of plastics. The problem is even greater when it comes to mixed plastics

The sorting of plastics must be characterized by high efficiency and purity of the obtained raw material, and the choice of the method of separating mixed plastic waste depends on the particle size, the form in which the waste occurs, and its source, the degree of contamination, etc. In order to improve the separation efficiency of waste plastics to be used with modern and fast instrumental techniques based on electrostatic methods.

1.1 Electrostatic plastic waste separation

Electrostatic separation is efficient method to separate not only plastics or metals (e.g. cables and electric wires, electronic equipment, household appliances, cars), but also organic materials such as wheat, grain, flour, roughage, protein, oilseeds, legumes and has been used on a large scale for over 60 years [13–21]. Currently, scientists in many research centers are working intensively on the development of modern electrostatic separation systems - separators - aiming their efforts to increase the effectiveness of the separation process. The design and principle of operation of the electrostatic separator (ES) depend on the type and physical properties of the input material being separated. Analyzing the scientific literature resources as well as patent descriptions, it can be concluded that there is a large number of different designs and methods of operation of electrostatic separators [18], [21–25]. In general, in terms of the principle of operation two major types of ES can be distinguished: (a) separators in which the difference of charge decay of the materials is utilized to perform separation and (b) separators utilising triboelectric phenomena. Despite these differences, several same components of ES can be distinguished, such as a charging device for electrifying the sorted material, a feeder, electrodes, and a high voltage system.

Electrostatic separation uses the forces of an electric field exerted on electrified particles (i.e. plastic granulates). Two major methods of electrifying particles such as mechanical triboelectrification and corona charging can be distinguished. The most common subject of scientific and industrial research related to plastics is mechanical triboelectrization in gas solid fluidized beds. In industrial applications is mechanical triboelectrization, i.e.

accumulation of electrostatic charge on its surface as a result of its friction with another material is the most common method to charge the plastic particles. [18–20, 26]. Despite many experimental and theoretical research of this process, due to its complexity in the atom scale, the phenomena of triboelectrization of plastics is still not fully recognized.

An alternative way for electrification particles is charging through corona discharge. The high voltage applied to the corona electrode causes ionization of the air in its vicinity. Plastic particles in the area of ionization are charged [27–34]. Charging can occur directly on the drum or belt. Then, charged particles are transported on the rotating part of the separator. On the drum, particles with good conductivity (conductors or materials with a short charge decay time) lose the acquired charge and are "thrown" from the drum surface by centrifugal force, additionally, deflection electrodes are used, causing a deflection of the trajectory of the ejected particles. Materials with poor conductivity and long charge decay time, retain the obtained charge and are mechanically ejected from the drum surface (by additional brushes or as a result of centrifugal force and gravity). Corona discharge electrification is successfully used in the separation of waste plastic mixtures containing contamination with metal particles [35, 36].

In electrostatic separation processes, regardless of the way they are carried out, and in separators, regardless of the differences in their design, the forces acting on charged particle can be described by equation (1) [34]:

$$\boldsymbol{F}_e = 2\pi r^3 \varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \nabla \boldsymbol{E}^2 + q\boldsymbol{E} \qquad (1)$$

where: $\boldsymbol{F}_e$ is the electric force [N], r is the radius of the particle, $\varepsilon_1$is the relative permittivity of the particle, ε_2 is the relative permittivity of the medium, $\boldsymbol{E}$is the electric field intensity [$\mathrm{V \cdot m^{-1}}$], q is the electric charge of the particle [C].

In equation (1), the first component determines the force of diaphoresis appearing only in inhomogeneous fields, and its use for separation purposes is difficult, as it requires high gradients of an electric field, which creates technical difficulties [34]. The second component of this equation determines the force of electrophoresis acting on the electrified particle. Most of the separators used in laboratories and in the industry are based on the phenomenon of electrophoresis.

The designs of separators presented in the literature can be divided into two groups: free-fall separators (Fig. 1a, 1b) and separators with a rotating electrode (Fig.2, 3). Free-fall triboelectrostatic separators are characterized by the fact that the particles of electrified material fall freely in the electrostatic field of the separation system. The most common structure of a free separator is a separator consisting of two parallel positive and negative electrodes (Parallel Plate). Material input is charged in additional device or chamber where triboelectric charging occurs.

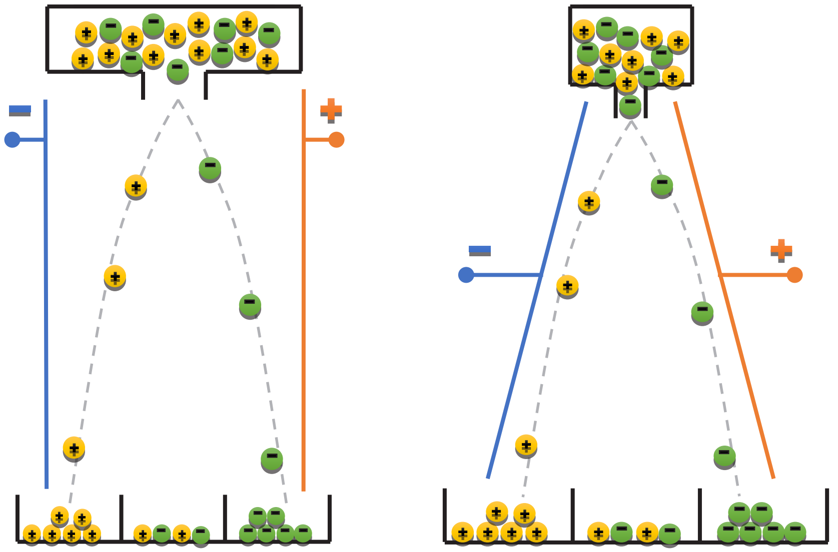

Fig. 1. Typical configuration of a free-fall triboelectrostatic separator a) parallel plate and b) skew plate.

The separation of tribocharged mixtures is carried out in an electrostatic field between two electrodes, e.g. a high voltage electrode and a grounded electrode. The particle carrying the charge q placed in this field of electric intensity $\boldsymbol{E}$ is affected by the force $\boldsymbol{F}$, which according to electric field intensity definition can be determined as $\boldsymbol{E} = \boldsymbol{F}/q$ [28]. Triboelectrification in a fluidized bed is a type of mechanical triboelectrification, where the friction takes place in a fluidized bed and in the air stream flowing through it [32, 37].

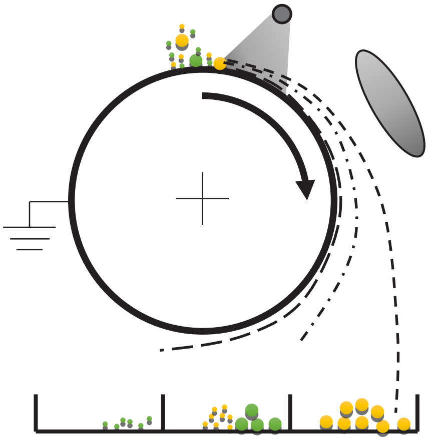

Fig. 2. Typical configuration of a high tension roll separator.

Two common types of rotating electrode separators are drum (roller) or belt separator. They are the most common designs that can be found studied in the literature [19, 21, 22, 25, 38]. Particle charging mechanisms are mainly based on the corona discharge effect, however these separators can be also fed with tribocharged material.

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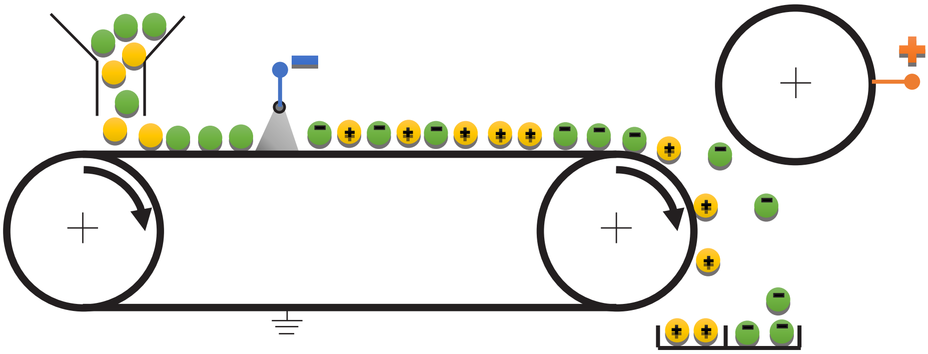

Fig. 3. Typical configuration of a high tension belt separator.

2 Concept and Design of the test stand

The effectiveness of the separation process depends on many factors. Based on literature studies and theoretical background it can be stated that impact on the effectiveness of this process has among others, location of the electrodes, voltage value, drum and feeder speeds as well as parameters influencing the tribocharging process like the humidity of material, temperature, air pressure, etc.[28, 34, 35]. In general, the availability of the advanced numerical methods of computer simulation of electrostatic field distribution, for instance finite element method, FEM, allowing to formulate and solve models of phenomena occurring in the separator should lead to omitting necessity of building the prototypes and carrying out expensive experimental research. Nevertheless, still the biggest problem related to the simulation of the electrostatic separation is the issue of identification of model parameters. In practice, the input material for the separation has a form of granules of different shapes and sizes affecting the balance of the forces. Moreover, electric properties of the granules like charge decay, surface resistivity as well as electric permeability often are not known in advance and may vary even for the materials of the same type due to imposition in their production process ingredients modifying their electric properties. Out of the discussed above reasons the research on the electrostatic separation process is often supported by experimental studies. Often the set of separation process parameters of a given pair of materials are identified initially on the basis of the simulation studies and next verified and optimized on the test stand by experimental testing the influence of particular parameters. The experimental research on the effectiveness of the electrostatic separation process can be seen in the perspective of the typical optimization process in which the values of design parameters (voltage,electrode location, etc.) are sought to maximize the goal function (quality and throughput of separator). There are many effective optimization methods that could be applied in solving such problems. Nevertheless, even applying modern nature inspired optimization algorithms, like a bat or grey wolf algorithms, taking into account a high number of degrees of freedom - design variables number of goal function evaluations (tests performed on the stand) is very high. Out of the discussed reasons, the development of dedicated and automated test stand allowing to perform a high number of material separation tests for different process parameters is necessary.

The paper presents an innovative design of a test stand developed by the authors for the research on plastics waste electrostatic separation. The proposed system is equipped with an own developed computer vision system for analyzing the impact of process parameters (electrode position, polarity and voltage control, variable speed of the feeder and drum, as well as triboelectrification parameters) on the separation efficiency of plastics. The application of the vision system enables fast assessment of the quality of the separation. The overall concept of the proposed system is shown in Fig. 4.

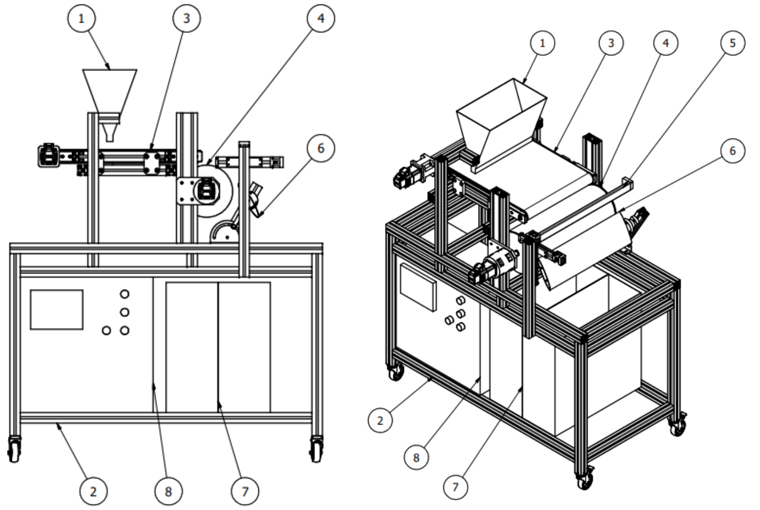

Fig. 4. Side and isometric view of the designed ES system: 1 - material feeder, 2 - aluminum frame, 3 - belt transporter, 4 - rotating drum, 5 - corona electrode, 6 - deflection electrode, 7 - material collectors, 8 - electrical cabinet

The applied CAD methods allow us to predict the shape of every part and any dimensions of the ES. The backbone frame of the construction is based on prefabricated aluminium profiles and it is assembled as one structure (2). Due to the application of prefabricated aluminium profiles any connections changes and corrections, if needed, can be made quickly. Main parts of the ES were designed in a modular way. Fedder (1) can be easily adapted as a free fall hopper, a vibration fedder device, or as a tribocharging bed. The amount of material fed from the hopper is adjustable. The next main part of the system is a belt conveyor (3), where input material is transported from the fedder to the rotating drum. The belt is driven by a servo motor with additional mechanical transmission. The application of advanced industrial servo drive allows precise control of the linear speed of the belt, which can be changed in an easy way.

The principle of operation of the separator is based on a rotating drum (4) which is on the ground potential. The drum rotation is forced by the servo motor connected directly to the shaft through the elastic clutch. The fedder as well as the drum servo motors are driven by the separate inverters controlled by a Siemens PLC. The proposed ES test rig is equipped with two high voltage electrodes: corona and deflection. Corona electrode (5) is mounted on two linear actuators that give the possibility of positioning the whole stage in relation to the drum in the X and Y axes coplanar to the drum base. Linear actuators with stepper motors can hold the specific setpoint of the electrode position during the separation process. The deflection electrode (6) is mounted on a movable and adjustable holder. The position and rotation of this part can be changed manually.

Container collectors (7) for separated material are located under the drum, inside of the frame. To facilitate the emptying of the container, they were attached to a linear cart. The container has been divided into equal chambers. After each separation process, the whole cart can be pulled out, so the result of the experiment can be easily analyzed by the developed vision system and the research can be repeated. Next to the material collectors, the electrical cabinet (8) is mounted. Whole electrical equipment of the ES such asPLC, inverters, stepper motor drivers, and high voltage power supply is placed inside. Due to the

high voltages in the range of 5 to 60 kV the cabinet and frame are isolated from the power supply. The high voltage applied to the electrodes has been provided through a special highly insulated wires.
In order to assess the potential risk of damage of the control equipment (servo drives as well as the electrode positioning system) by the presence of the high voltage the numerical model of the electric field in the designed ES has been elaborated in the Ansys Maxwell environment. Application of the Finite Element Method (FEM) allows determining the electric field distribution in the studied separator and has been used to define the insulation system of the designed ES. The exemplary electric field lines distribution for electrode voltage equal to 20kV has been shown in Fig. 5.

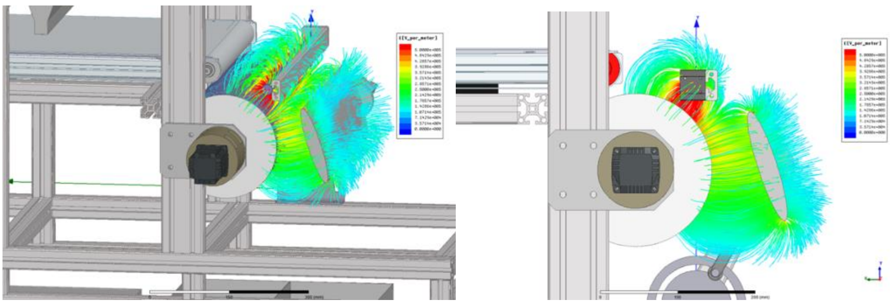

Fig. 5. Distributions of the electric field excited by the corona and deflection electrodes at 20kV.

3 Conclusions and Future Work

The paper presents and discusses an innovative design of an automated test stand developed by the authors for the research on plastics waste electrostatic separation. The design of the proposed system has been based on literature studies as well as carried out numerical simulations employing FEM. In order to provide the ability of effective testing of the impact of a high number of parameters of electrostatic separation process (electrode position, polarity, and voltage control, speed of the feeder and drum, as well as triboelectrification and/or corona electrification parameters) the designed test stand has been equipped with own developed computer vision system for analyzing the impact of process parameters on the separation efficiency of mixed plastics waste. The application of the vision system enables a fast assessment of the quality of the separation.
Currently the developed test stand has been built and commissioned, the preliminary tests of separation process performed on poly(methyl methacrylate) -PMMA and polystyrene (PS) mixture confirms high research potential of the developed ES test stand. The results presented in this article are the beginning of the research focused on the development of separation techniques difficult to separate mixtures of polymer and the results will be the scope of the further scientific publications of authors.

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References

1. J. Flizikowski, M. Macko Competitive design of shredder for plastic in recycling. Tools Methods Compet. Eng. 1, 1147–1148 (2004).
2. Ł. Warguła, M. Kukla, P. Krawiec, B. Wieczorek Reduction in Operating Costs and Environmental Impact Consisting in the Modernization of the Low-Power Cylindrical Wood Chipper Power Unit by Using Alternative Fuel. Energies. 13, 2995 (2020).
3. D. Czarnecka-Komorowska, K. Wiszumirska Sustainability design of plastic packaging for the Circular Economy. Polimery. 65, 8–17 (2020).
4. D. Czarnecka-Komorowska, K. Wiszumirska, T. Garbacz Films LDPE/LLDPE made from post–consumer plastics: processing, structure, mechanical properties. Adv. Sci. Technol. Res. J. 12 (2018).
5. Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles - Commission Statements, https://eur-lex.europa.eu/legal-content/PL/ALL/?uri=CELEX%3A32000L0053 - access 26.02.2020.
6. End-of-life vehicle statistics - Eurostat, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=End-of-life_vehicle_statistics - access 26.02.2020.
7. M. Macko, Z. Szczepanski, E. Mikolajewska, J. Nowak, D. Mikolajewski Repository of 3D images for education and everyday clinical practice purposes. Bio-Algorithms Med-Syst. 13, 111–116 (2017).
8. K. Gawdzinska, M. Nabialek, A.W. Sandu, K. Bryll The choice of recycling methods for single-polymer polyester composites, Materiale Plastice 55, 658–665 (2018).
9. G. Dodbiba, T. Fujita Progress in separating plastic materials for recycling. Phys. Sep. Sci. Eng. 13, 165–182 (2004).
10. S.A. Pradeep, R.K. Iyer, H. Kazan, S. Pilla Automotive applications of plastics: past, present, and future. In: Applied Plastics Engineering Handbook. pp. 651–673. Elsevier (2017).
11. X. Yang, X. Liu, L. Song, C.Y. Lv, X. Cheng Study on the separators for plastic wastes processing. Procedia Eng. 174, 497–503 (2017).
12. S. Serranti, G. Bonifazi Techniques for separation of plastic wastes. In: Use of Recycled Plastics in Eco-efficient Concrete. pp. 9–37. Elsevier (2019).
13. K.C. Lai, S.K. Lim, P.C. Teh, K.H. Yeap An Artificial Neural Network Approach to Predicting Electrostatic Separation Performance for Food Waste Recovery. Pol. J. Environ. Stud. 26, 1921–1926 (2017).
14. J. Wang, M. de Wit, R.M. Boom, M.A.I. Schutyser Charging and separation behavior of gluten–starch mixtures assessed with a custom-built electrostatic separator. Sep. Purif. Technol. 152, 164–171 (2015). https://doi.org/10.1016/j.seppur.2015.08.025.
15. S. Tabtabaei, D. Konakbayeva, A.R. Rajabzadeh, R.L. Legge Functional properties of navy bean (Phaseolus vulgaris) protein concentrates obtained by pneumatic tribo-electrostatic separation. Food Chem. 283, 101–110 (2019).
16. J. Wang, J. Zhao, M. de Wit, R.M. Boom, M.A.I. Schutyser Lupine protein enrichment by milling and electrostatic separation. Innov. Food Sci. Emerg. Technol. 33, 596–602 (2016).
17. A. Iuga, L. Calin, V. Neamtu, A. Mihalcioiu, L. Dascalescu Tribocharging of plastics granulates in a fluidized bed device. J. Electrost. 63, 937–942 (2005).
18. L. Calin, L. Caliap, V. Neamtu, R. Morar, A. Iuga, A. Samuila, L. Dascalescu Tribocharging of Granular Plastic Mixtures in View of Electrostatic Separation. IEEE Trans. Ind. Appl. 44, 1045–1051 (2008).
19. M. Żenkiewicz, T. Żuk, J. Pietraszek Modeling electrostatic separation of mixtures of poly(ε-caprolactone) with poly(vinyl chloride) or poly(ethylene terephthalate). (2016).

20. A. Cieśla Elektryzacja ziaren węgla metodą tryboelektryczną. Przegląd Elektrotechniczny. 1, 131–134 (2017).
21. H. Lu, J. Li, J. Guo, Z. Xu Movement behavior in electrostatic separation: Recycling of metal materials from waste printed circuit board. J. Mater. Process. Technol. 197, 101–108 (2008)..
22. H.M. Veit, T.R. Diehl, A.P. Salami, J.S. Rodrigues, A.M. Bernardes, J.A.S. Tenório, J.A.S.: Utilization of magnetic and electrostatic separation in the recycling of printed circuit boards scrap. Waste Manag. 25, 67–74 (2005).
23. U. Śliwa, M. Skowron Analysis of the electric field distribution in the drum separator of different electrode configuration. Inform. Autom. Pomiary W Gospod. Ochr. Śr. 6, 79–82 (2016).
24. L. Dascalescu, T. Zeghloul, A. Iuga, A. Chapter 4 - Electrostatic Separation of Metals and Plastics From Waste Electrical and Electronic Equipment. In: Chagnes, A., Cote, G., Ekberg, C., Nilsson, M., Retegan, T., Chagnes, A., Cote, G., Ekberg, C., Nilsson, M., and Retegan, T. (eds.) WEEE Recycling. pp. 75–106 (2016).
25. G. Bedeković, B. Salopek, I. Sobota Electrostatic separation of PET/PVC mixture, Tehnički vjesnik 18, 261-266 (2011).
26. T. Zeghloul, A. Mekhalef Benhafssa, G. Richard, K. Medles, L. Dascalescu Effect of particle size on the tribo-aero-electrostatic separation of plastics. J. Electrost. 88, 24–28 (2017).
27. A. Benabderrahmane, K. Medles, T. Zeghloul, P. Renoux, L. Dascalescu, A. Parenty Triboelectrostatic separation of brominated flame retardants polymers from mixed granular wastes. In: 2019 IEEE Industry Applications Society Annual Meeting. pp. 1–4, Baltimore, MD, USA (2019).
28. M. Zenkiewicz, T. Zuk Physical basis of tribocharging and electrostatic separation of plastics. Polimery. 59, 314–323 (2014).
29. Y. Wu, G.S.P. Castle, I.I. Inculet Induction charging of granular materials in an electric field. In: Conference Record of the 2004 IEEE Industry Applications Conference, 2004. 39th IAS Annual Meeting, 4, 2366–2372 (2004).
30. F. Portoghese, F. Berruti, C. Briens Continuous on-line measurement of solid moisture content during fluidized bed drying using triboelectric probes. Powder Technol. 181, 169–177 (2008).
31. J.-K. Lee, J.-H. Shin, Y.-J. Hwang Triboelectrostatic separation system for separation of PVC and PS materials using fluidized bed tribocharger. KSME Int. J. 16, 1336–1345 (2002).
32. L. Dascalescu, O. Fati, M. Bilici, F. Rahou, C. Dragan, A. Samuila, A. Iuga Factors that influence the efficiency of a fluidized-bed-type tribo-electrostatic separator for mixed granular plastics. J. Phys. Conf. Ser. 301, 012066 (2011).
33. L. Dascalescu, A. Mizuno, R. Tobazeon, P. Atten, R. Morar, A. Iuga, M. Mihailescu, A. Samuila Charges and forces on conductive particles in roll-type corona-electrostatic separators. IEEE Trans. Ind. Appl. 31, 947–956 (1995).
34. A. Cieśla, W. Kraszewski, M. Skowron, A. Surowiak, P. Syrek Application of electrodynamic drum separator to electronic wastes separation. Gospod. Surowcami Miner. 32, 155–174 (2016).
35. Y.E. Prawatya, M.B. Neagoe, T. Zeghloul, L. Dascalescu Surface-Electric-Potential Characteristics of Tribo- and Corona-Charged Polymers: A Comparative Study. IEEE Trans. Ind. Appl. 53, 2423–2431 (2017).
36. Y. Prawatya, B. Neagoe, T. Zeghloul, L. Dascalescu Comparison between the surface-electric-potential characteristics of tribo- and corona-charged polymers. In: 2015 IEEE Industry Applications Society Annual Meeting. pp. 1–5 (2015).

37. L. Calin, A. Mihalcioiu, A. Iuga, L. Dascalescu Fluidized Bed Device for Plastic Granules Triboelectrification. Part. Sci. Technol. 25, 205–211 (2007).
38. A.G. Kyle Flynn, M. Frank Hrach Electrostatic-Separation-of-Dry-Granular-Food-Material-R4.pdf. Inż. Miner. J. Pol. Miner. Eng. Soc. 63–76 (2011).