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Automated test bench for research on electrostatic separation in plastic recycling application

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Abstract. Many researchers in the developed countries have been intensively seeking effective methods of plastic recycling over the past years. Those techniques are necessary to protect our natural environment and save non-renewable resources. This paper presents the concept of an electrostatic separator designed as a test bench dedicated to the separation of mixed plastic waste from the automotive industry. According to the current policy of the European Union on the recycling process of the automotive industry, all these waste materials must be recycled further for re-entering into the life cycle (according to the circular economy). In this paper, the proposed concept and design of the test bench were offered the feasibility to conduct research and technological tests of the electrostatic separation process of mixed plastics. The designed test bench facilitated assessing the impact of positions of high-voltage electrodes, the value and polarity of the high voltage, the variable speed of feeders and drums, and also triboelectrification parameters (like time and intensity) on the process, among others. A specialized computer vision system has been proposed and developed to enable quick and reliable evaluation of the impact of process parameters on the efficiency of electrostatic separation. The preliminary results of the conducted tests indicated that the proposed innovative design of the research stand ensures high research potential, thanks to the high accuracy of mixed plastics in a short time. The results showed the significant impact of the corona electrode position and the value of the applied voltage on the separation process effectiveness. It can be concluded that the results confirmed the ability to determine optimally the values of the studied parameters, in terms of plastic separation effectiveness. This study showed that this concept of an electrostatic separator designed as a test bench dedicated for separation of mixed plastic waste can be widely applied in the recycling plastic industry.

Key words: recycling; automotive plastics waste; separation; electrostatic separator.

1. Introduction

Nowadays, we see growing interest in plastic recycling for ecological, economical and legal reasons. Many efforts are carried out in this direction, especially regarding the car manufacturing industry [1–4]. The utilization of plastics in the automotive sector increases. The application of various types of polymers leads to a reduction in the number of cars and, as a consequence, to a decrease in greenhouse gasses (GHG) emissions by lowering fuel consumption. Legalized on 18th September 2000, the European Parliament Directive 2000/53/EC established the rules for dealing with end-of-life vehicles (ELVs), including the desired rates of recovery, reuse, and recycling of the materials utilized for their production [5]. In 2017, for example, about 88% of parts and materials of ELVs in the EU were reused and recycled, according to [6]. The regulations force producers to be responsible in the field of material recycling processes and support the development of the market of recycled materials towards a 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 effective and low-cost methods and technologies for recycling plastic waste [1, 2, 7, 8]. Providing such methods and technologies will allow one to treat polymer waste as a valuable secondary material that can be recycled into the production of various car parts like headlights, airbags, bumpers, radiator grills, and carpeting, among others.

The processes of segregation and separation are the basic steps in the preparation of polymer waste for recycling. Regarding the automotive industry, the problems with effective recycling are caused mainly by a large variety of plastics that require separation after the degradation of functional parameters [9, 10]. The most common plastic materials used in the automotive sector include polycarbonate (PC), polypropylene (PP), polyurethane (PU), polyamide (PA), polyvinyl chloride (PVC), polyformaldehyde (POM), acrylonitrile-butadiene-styrene (ABS), as well as poly (methyl methacrylate) – (PMMA),

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thermoset composites, thermoplastic polyester poly (butylene terephthalate) – (PBT) and poly (ethylene terephthalate) – (PET) [11]. In the mixed form, they are often immiscible blends preventing further processing; therefore, it is necessary to separate them into different fractions.

The process of sorting out plastics consists of separating the multicomponent system (mixture) into fractions that differ in physical properties. The cyclone separators or sink-flotation methods rely on the differences between the particle sizes and density. The difference in magnetic permeability and electrical conductivity is the base of the magnetic separation, while different electrical properties of materials facilitate performing electrostatic separation [4, 12, 13]. One of the problematic processes of modern waste management is the technologically and economically ineffective separation of plastics. The problem is even greater when it comes to plastic mixtures.

The sorting of plastics mixtures must be characterized by the 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, modern and fast instrumental techniques based on electrostatic methods should be used.

1.1. Electrostatic separation of plastic waste. An electrostatic separation is an effective approach allowing one 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. In the above-discussed applications, electrostatic separation has been used on a large scale for over 60 years [14–22]. Currently, scientists in many research centers all over the world are working intensively on the development of modern electrostatic separation systems for plastic waste (separators) putting their efforts into increasing the effectiveness of the separation process [23–25]. The design and principle of operation of the electrostatic separator (ES) depend on the type and physical properties of the input material being separated. Based on the review of the scientific literature as well as patent descriptions, it can be stated that there is a large number of different designs of electrostatic separators [19, 22, 26–29]. However, in terms of the principle of operation, two major types of ESs can be distinguished: (a) separators in which the difference of charge decay of the materials is exploited, and (b) separators utilizing triboelectric phenomena. Despite these differences, several of the same components of the ES can be distinguished, such as a charging device for electrifying the sorted material, a feeder, electrodes, and a high-voltage system.

The principle of operation of the ES is based on the phenomena of the occurrence of the electric forces exerted on the electrified particles (i.e. plastic granulates), exposed to the electric field. In general, the sorted particles can be charged by mechanical triboelectrification and/or by corona charging phenomena. The most common method exploited in the scientific and industrial research related to plastics separation is mechanical triboelectrification in gas- solid fluidized beds [18, 24, 30]. In general, the process of triboelectrification of the materials is understood as the accumulation of electrostatic charge on a particle surface as a result of its friction with another material [19–21, 31]. Despite much experimental and theoretical research on this process, due to its complexity in the macroscopic and atom scale, the phenomena of triboelectrification of plastics are still not well understood [32–34].

An alternative way to electrify plastic particles is by charging them through the corona discharge. The high voltage applied to the corona electrode causes the ionization of the air in its vicinity. Plastic particles in the area of ionization are charged [24, 25, 35–40]. Charging can occur directly on the drum or belt of the separator. Then, the charged particles are transported on the rotating part of the separator. The particles on the drum, which have good conductivity (conductors or materials with a short charge decay time), lose the acquired charge and are "thrown" from the drum surface by the 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 the centrifugal force and gravity). Corona discharge electrification is successfully used in the separation of waste plastic mixtures containing metal particles [41, 42].

In electrostatic separation processes, regardless of the method of charging the particles, and differences in the separator design, the electric forces acting on a charged particle can be described by [25]:

$$\mathbf{F}_e = 2\pi r^3 \varepsilon_1 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 - 2\varepsilon_1} \nabla \mathbf{E}^2 + q\mathbf{E}, \tag{1}$$

where: $\mathbf{F}_e$ is the electric force [N]; r is the radius of the particle; ε_1 is the relative permittivity of the particle; ε_2 is the relative permittivity of the medium; $\mathbf{E}$ is the electric field intensity $\left[\mathrm{V \cdot m^{-1}}\right]$; q is the electric charge of the particle [C].

The first component in Eq. (1) determines the force $(\mathbf{F}_e)$ of diaphoresis appearing only in inhomogeneous fields. The exploitation of this force for separation purposes is difficult, as it requires high gradients of an electric field, which creates a number of technical difficulties [25]. The second component of this equation determines the force of electrophoresis acting on the electrified particles. Most of the separators used in laboratories and the industry are based on the phenomenon of electrophoresis forces.

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

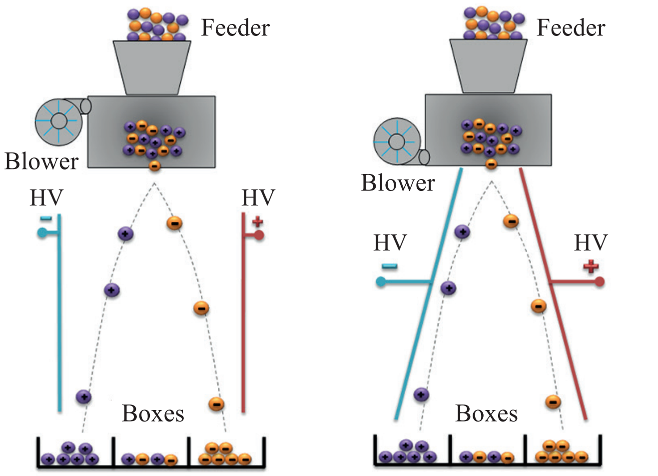


Fig. 1. The typical configuration of free-fall triboelectric separators: a parallel plate (left) and skew plate (right), with an air blower as an example of a tribo-charger

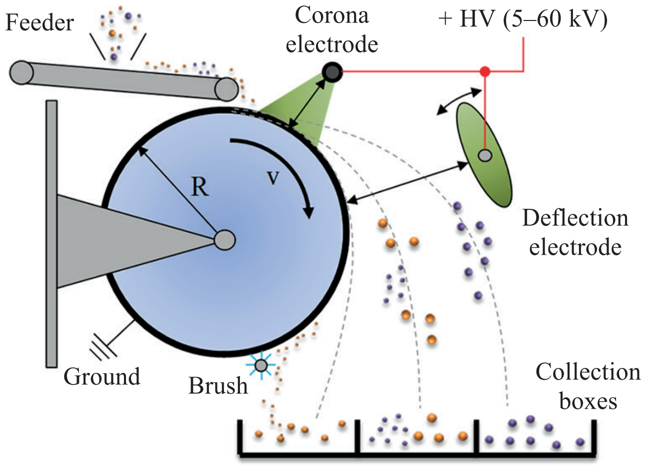


Fig. 2. Crucial elements and dimensions influencing the separation process in the typical configuration of a rotating electrode drum type separator

The separation of tribo-charged mixtures is carried out in an electrostatic field between two electrodes, e.g. a high-voltage electrode and a grounded electrode. The trajectory of the free-falling particle carrying the charge q in the electric field of the intensity $\mathbf{E}$ is affected by the force $\mathbf{F}_e$, which, according to (1), can be determined as $\mathbf{F}_e = q\mathbf{E}$. Negatively and positively charged particles of a triboelectric pair of materials are attracted to the electrodes of the opposite potential, respectively. The triboelectrification in a fluidized bed is a type of mechanical triboelectrification, where friction occurs when an airstream flows through such a bed [24, 30].

The trajectory of the charged particles in the rotating electrode separators (see Fig. 2) is more complex. Besides the gravity $\boldsymbol{F}_g$ and electric $\boldsymbol{F}_e$ forces, the centrifugal force $\boldsymbol{F}_c$ and electric induced charge force $\boldsymbol{F}_i$ acting on the particle must be considered. The resultant force $\boldsymbol{F}$, allowing one to determine the particle trajectory, can be expressed by the following formula [25, 43]:

$$\mathbf{F} = m\mathbf{g} + q\mathbf{E} + m\boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{R}) - \frac{q^2}{4\pi\varepsilon_0(2r)^2}\mathbf{1}_\mathbf{R}, \qquad (2)$$

where: m is the mass of the particle; $\mathbf{R}$ is the radius of the drum; ε_1 is the dielectric constant of the air.

Considering the particle velocity $\mathbf{v}$, the differential equation of mechanical equilibrium is as follows:

$$\mathbf{F} = m\frac{d\mathbf{v}}{dt}, \qquad (3)$$

The most common designs of rotating electrode separators that were found in the studied literature [20, 22, 26, 29, 44] are drum (a roller type – example shown in Fig. 2) and belt type separators. Particle-charging mechanisms are mainly based on the corona discharge effect; however, these separators can be also fed with a tribo-charged material.

2. Automated test stand concept

The process of electrostatic separation is influenced by a high number of factors such as voltage value, electrical properties of sorted materials, the shape and position of electrodes, drum as well as feeder speed. Other important parameters are the moisture content of the material, temperature, air pressure (the tribo- and/or corona charging phenomena) [25, 36, 41].

Despite the simplicity of the model of charged particle motion in the presence of an electric field formulated in Section 1.1, the prediction of their trajectories in real devices is a complex and challenging task, mainly due to the difficulties in the identification of the model parameters. In general, the sizes and shapes of the particles can differ significantly in the sorted material. Moreover, the charge of the particle resulting from the corona discharge process and/or triboelectrification process can be estimated only with certain accuracy due to charge decay, which is time dependent. Furthermore, the electrical properties of the granules, such as charge decay, surface resistivity, and electrical permeability, are often unknown. Differences may also appear in the materials of the same type. These differences are often the result of the manufacturing processes described in [45]. Despite the availability of advanced numerical methods for the computer simulation of electrostatic field distribution, for instance, the finite element method (FEM) that facilitates formulating and solving models of phenomena occurring in the separator, the research on electrostatic separation is still necessary to build the prototypes and carry out expensive experimental studies. For the above reasons, the research on the electrostatic separation process is very often supported by experimental studies. Typically, the parameters of the separation process for a given pair of materials are initially identified based on the simulation studies and in the next stage of the research, optimization methods they are verified and optimized on the test stands by the experimental evaluation of the influence of individual parameters. The experimental research on the effectiveness of the electrostatic separation process can be seen from the perspective of a 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 separation). Many effective optimization methods could be applied to solve such problems. Nevertheless, even applying modern, nature-inspired optimization algorithms, like bat or grey wolf algorithms [46–48], considering high number process parameters (defining the search space), the number of goal function evaluations (tests performed on the stand) is very high. Therefore, to enable the research on the electrostatic separation of plastic materials, the development of a dedicated and automated test stand allowing one to perform a high number of tests for different process parameters is necessary.

The authors described a fully automated test stand dedicated to the experiments with plastic waste separation. The test stand structure is presented in Fig. 3. In order to analyze the separation efficiency, a dedicated vision system developed by the authors was used. The vision system application allowed for a quick assessment of the impact of particular parameters on the degree of separation in the separation process.

The test stand has been designed using professional CAD methods allowing one to predict the shape of every part and any dimensions of the ES. The design was carried out in the

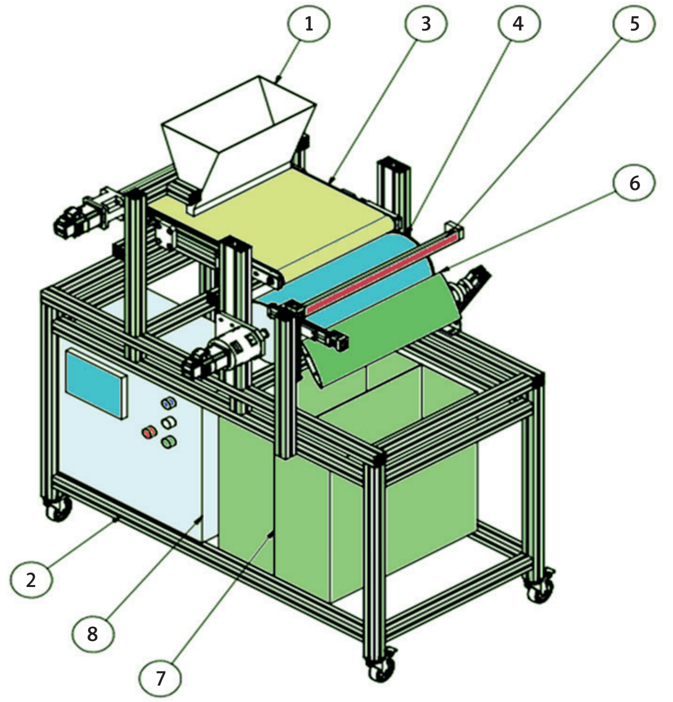


Fig. 3. Isometric view of the designed ES system: 1 – material feeder, 2 – aluminum frame, 3 – belt transporter, 4 – rotating drum, 5 – corona electrode, 6 – deflection electrode, 7 – material collectors, 8 – electrical cabinet

Autodesk Inventor CAD environment. The backbone frame of the construction is based on the prefabricated aluminum profiles and it is assembled as one structure (2). The application of the prefabricated aluminum profiles gives the possibility to introduce any changes to connections and corrections of the positions of main components if needed. The proposed ES was built in a modular way. The feeder (1) can be easily converted into a free-fall hopper, a vibration feeder device, or a tribo-charging bed. The device allows for adjusting the amount of the material fed. The next important part of the system is the belt conveyor (3) which is responsible for transporting the input material from the feeder to the rotating drum. The conveyor is driven by a precise industrial servo motor with mechanical gear. The application of an advanced industrial servo drive allows for the precise control of the linear speed of the belt.

The particles from the belt conveyor are transported to the rotating drum (4). The drum is connected to the ground potential. The drum position is controlled by the second servo motor (connected directly to the shaft through the elastic clutch). Both servo motors are connected to inverters controlled by the industrial programmable logic controller (PLC). The test stand is equipped with corona and deflection high-voltage electrodes. The corona electrode (5) can move along two co-planar axes to the drum base. The use of the stepper motor enables maintaining the desired position during the separation process. The deflection electrode (6) has also the ability to change positions and rotation (manually). In the case when input material is tribo-charged, the corona electrode can be removed, and its automated positioning system can be utilized to control the location of the deflection electrode without manual operations. The separated material goes to the container for collectors (7) located under the drum. The container is divided into 18 segments. After each test, the container is removed and placed on the stand with the vision system. Due to the use of the linear card, this operation takes a short period. The electrical cabinet (8) is mounted next to the material collectors. The whole electrical equipment of the ES, such as the PLC, inverters, stepper motor drivers, and high-voltage (HV) power supply, is placed inside the cabinet. Due to the presence of high voltages in the range of 5 to 60 kV the cabinet and frame are isolated from the high-voltage power supply. The high voltage applied to the electrodes has been provided through special, highly insulated wires, ensuring proper distances from the conductive elements of the test stand.

A numerical model of the electric field of the designed device was developed in the Ansys Maxwell environment as part of the project. The application of the Finite Element Method (FEM) allowed for determining the electric field distribution in the studied separator and has been used to define the insulation system of the designed ES. The performed studies allowed one to reduce the potential risk of damage to the control system and to predict the safe location of HV cables. The distribution of exemplary electric field lines for the positions of the chosen electrodes and high voltage equals 20 kV, as shown in Fig. 4.

In the proposed design, it can be observed that the servo motor driving the drum as well as the corona electrode positioning system are not exposed to high voltage.

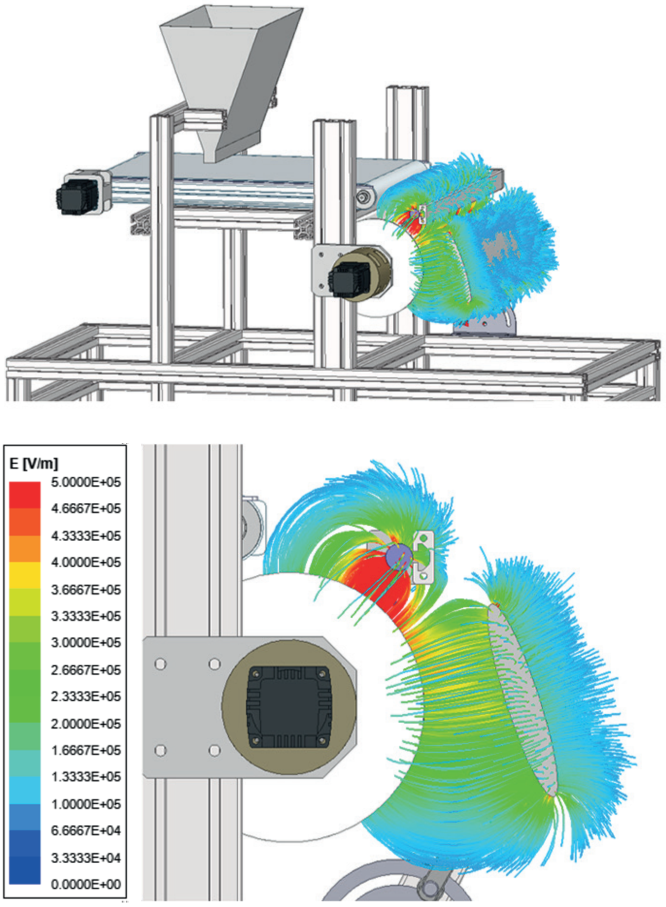


Fig. 4. The electric field distributions excited by the corona and deflection electrodes

Fig. 5. A prototype of an automated test stand for the electrostatic separation of plastic waste materials

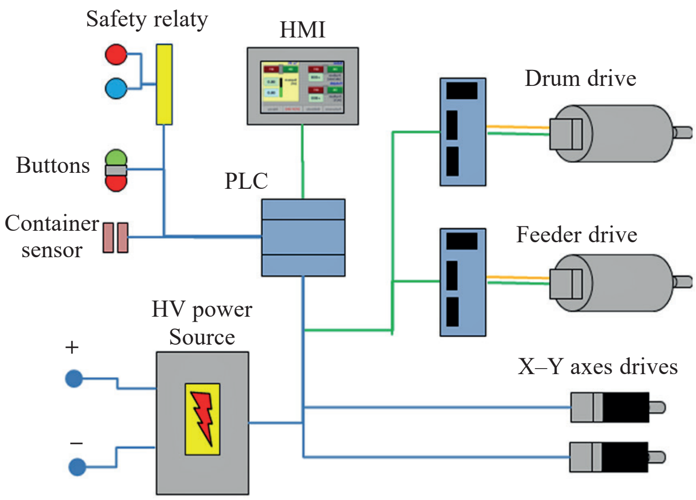


Fig. 6. Schematic view on the control system

3. Separator prototype and control algorithm

The prototype of the test bench was developed according to the concept proposed during the design process. Nevertheless, several minor changes to the initial design have been introduced. The current state of the system is presented in Fig. 5. The location of the control panel has been changed in order to ensure more ergonomic and easy access to the control functions. To reduce the risk of high voltage breakdown in the control system, the size of the main cabinet and its location is different as compared to the initial design.

The control system of the test stand has been developed using the Siemens Totally Integrated Automation Portal (TIA Portal) environment. In general, the algorithm of controlling the setup has been developed simultaneously with the preliminary tests and based on conducted literature studies regarding the electrostatic separation process. A schematic view of the developed control system of the test bench is shown in Fig. 6. The developed system consists of an industrial PLC unit equipped with a human-machine interface (HMI) panel, four-axis drives, an HV power source, a basic safety system, and additional controls and sensors (general purpose relays and light indicators). For the drum and the feeder drives, high-class industrial servo motors were used. For controlling the corona electrode position 2 axes, driven by stepper motors equipped with integrated electronics, were used.

4. Results of plastic mixture separation

To evaluate the usability of the designed test stand and the effectiveness of the separation process, various tests were conducted on the developed prototype. Firstly, all components of the test stand were adjusted to work properly within the desired range of process parameters. As a result of the performed mechanical and electrical tests, knowledge about the limits of the values of particular parameters was obtained.

The research carried out on the developed test stand was divided into two main stages. First, the impact of the value of the corona electrode voltage on separation effectiveness has been examined, then the influence of the corona electrode position on the constant voltage and critical value of the voltage has been tested.

To perform both stages, it was necessary to prepare a mixture of plastic waste, the composition of which was known. Plastics selected for this purpose were polystyrene (PS) and poly (methyl methacrylate) – PMMA.

The prepared mixture contained shredded yogurt cups and car lamp shades. After fragmentation, each material was sifted during a multi-stage process to obtain an appropriate gradation of particle sizes. To enable the application of the developed vision system to assess the effectiveness of the separation selected for the tests, the used materials had specific colors: white – PS and red – PMMA. To minimize the impact of particle sizes on the separation process in the presented research, the PS and PMMA particles of sizes 1.6 to 2.4 mm were separated.

The separation tests with the prepared waste mixture have been performed under 9 different conditions listed in Table 1. The methodology of those tests was to evaluate the impact of arbitrarily selected parameters on the effectiveness of the separation process: the high-voltage value and distance between the drum and corona electrodes. The drum rotational speed was constant and equal to 25 rpm, while the belt transporter speed equaled 100 mm/s.

Table 1
Parameters of the conducted tests

Test no.	Parameters		Results
	Electrode distance d [mm]	Corona electrode voltage U [kV]	SE [–]
1	–72	28.0	0.245
2	–72	30.5	0.521
3	–72	33.0	0.821
4	–72	35.5	0.760
5	–62	28.0	0.732
6	–62	30.5	0.855
7	–62	33.0	0.845
8	–52	28.0	0.827
9	–42	24.0	0.792

The performed tests allowed for studying the impact of (a) HV value and (b) the electrode position on the effectiveness of the separation process.

In the case of test a), two positions of the corona electrode have been examined (tests denote them as no. 1 to 7 in Table 1), while in the case of test b), the impact of the electrode position has been examined at the constant (tests no. 1, 5 and 8 from Table 1) and critical value of the high voltage (tests no. 4, 7, 8 and 9). The critical value of the high voltage at a given electrode distance *d* to the drum surface has been defined as the highest value of the voltage for which the breakdown discharge does not occur between the drum and the corona electrodes. This value was empirically estimated for the four studied positions of the corona electrode.

The results of the performed tests have been summarized in Fig. 9. The charts in the left column contain the accumulated bar plots of the raw data obtained from the developed vision system. These plots present the percentage content of PS and PMMA particles for each of 18 collectors of the material container (Region of Interest, ROI). As the interpretation of these plots does not provide the differences in the amounts of the sorted materials between particular ROIs, the assessment of the effectiveness of the separation process based on them is difficult. In order to illustrate the amount of the material and its location in ROIs, the radar plots shown in the middle column of Fig. 9 have been elaborated based on the raw data obtained from the dedicated vision system (percentage of the number of pixels in a specific color according to the HSV color palette). These plots provide the data on the percentage content of PMMA and PS materials in particular ROIs related to the sum of a given material in the test. The right column of Fig. 9 contains a photo of the material container for particular tests.

Based on the obtained results, the coefficient of the separation effectiveness *SE* has been calculated according to the following formula:

$$SE = \min(k_1, k_2), \text{ where } k_i = \frac{\sum_j m_{ij}}{tot_i}, \tag{4}$$

where: $i = 1$ and 2 for PS and PMMA materials, respectively. The sum of m_{ij} represents the amount of the particular material estimated by the vision system in each collector (ROI) where the majority of the percentage content of the i-th material is observed. The component tot_i in (4) represents the amount of the i-th material in all 18 collectors in the container.

The influence of the value of the high voltage applied to the corona electrode on the value of the *SE* coefficient has been illustrated in Fig. 7.

It can be observed that for each electrode positions the proposed approach allows one to determine the optimal value of the voltage applied to the corona electrode.

Next, the influence of the electrode position has been evaluated. Two cases have been examined, i.e. when the voltage of the corona electrode was kept constant (at a level of 28 kV) and when adjusted to its critical value. When studying the obtained characteristic of the *SE* coefficient shown in Fig. 8, it can be concluded that when using the proposed approach and equipment, the optimal electrode position for the critical value of the voltage can be determined.

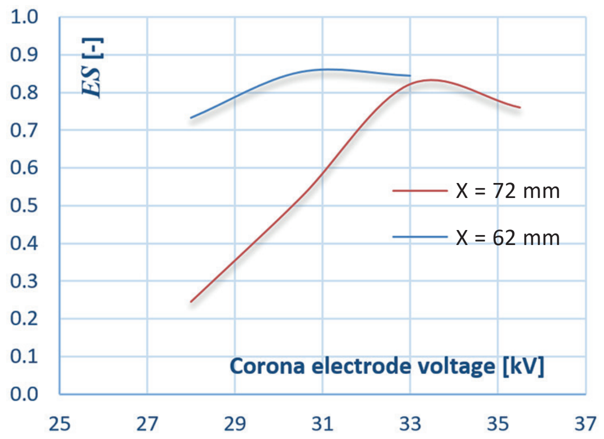


Fig. 7. The influence of the high voltage value on the separation effectiveness coefficient

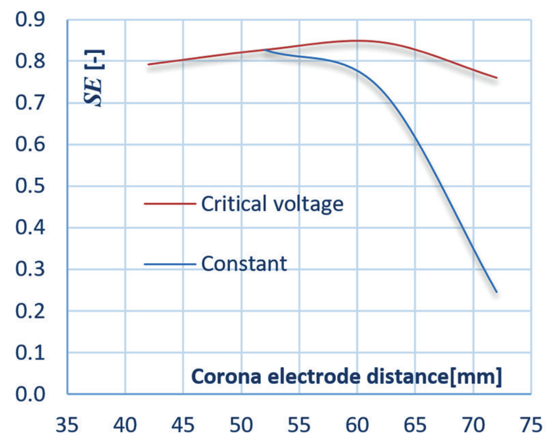


Fig. 8. The influence of the corona electrode position at constant and critical values of the voltage on the separation effectiveness coefficient

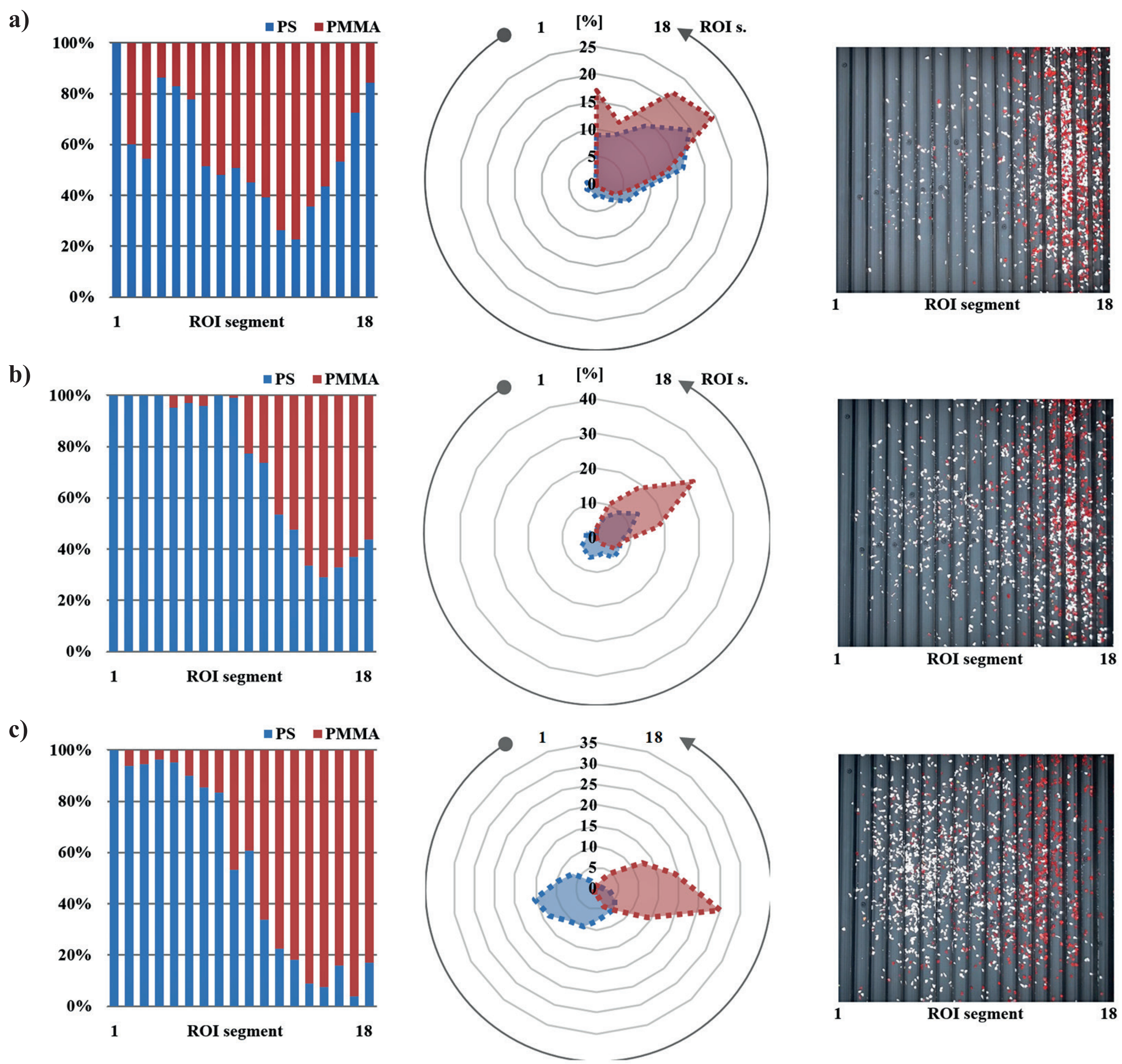
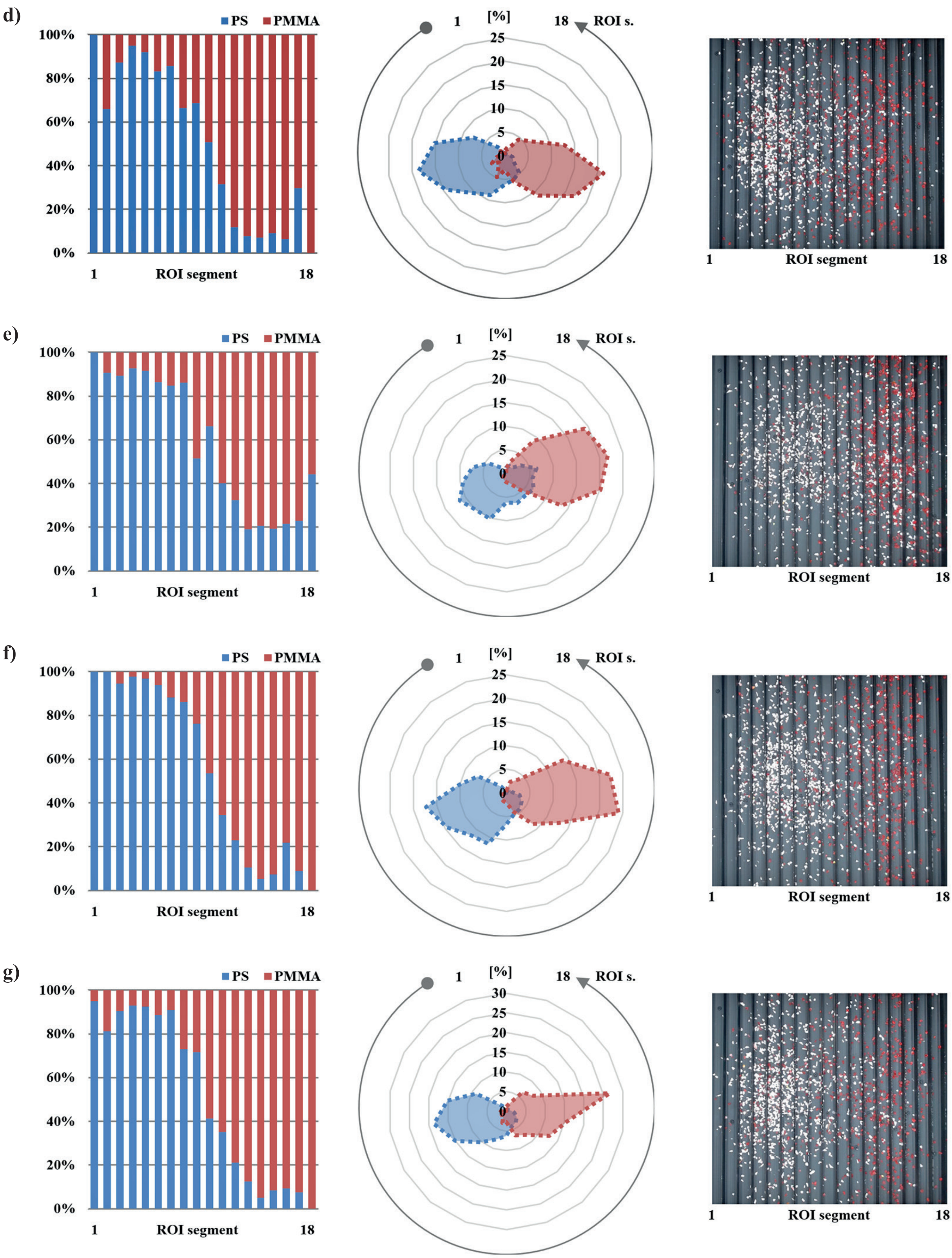


Fig. 9. Results of performed tests for PMMA and PS separation from (a) to (i) correspond to test numbers in Table 1



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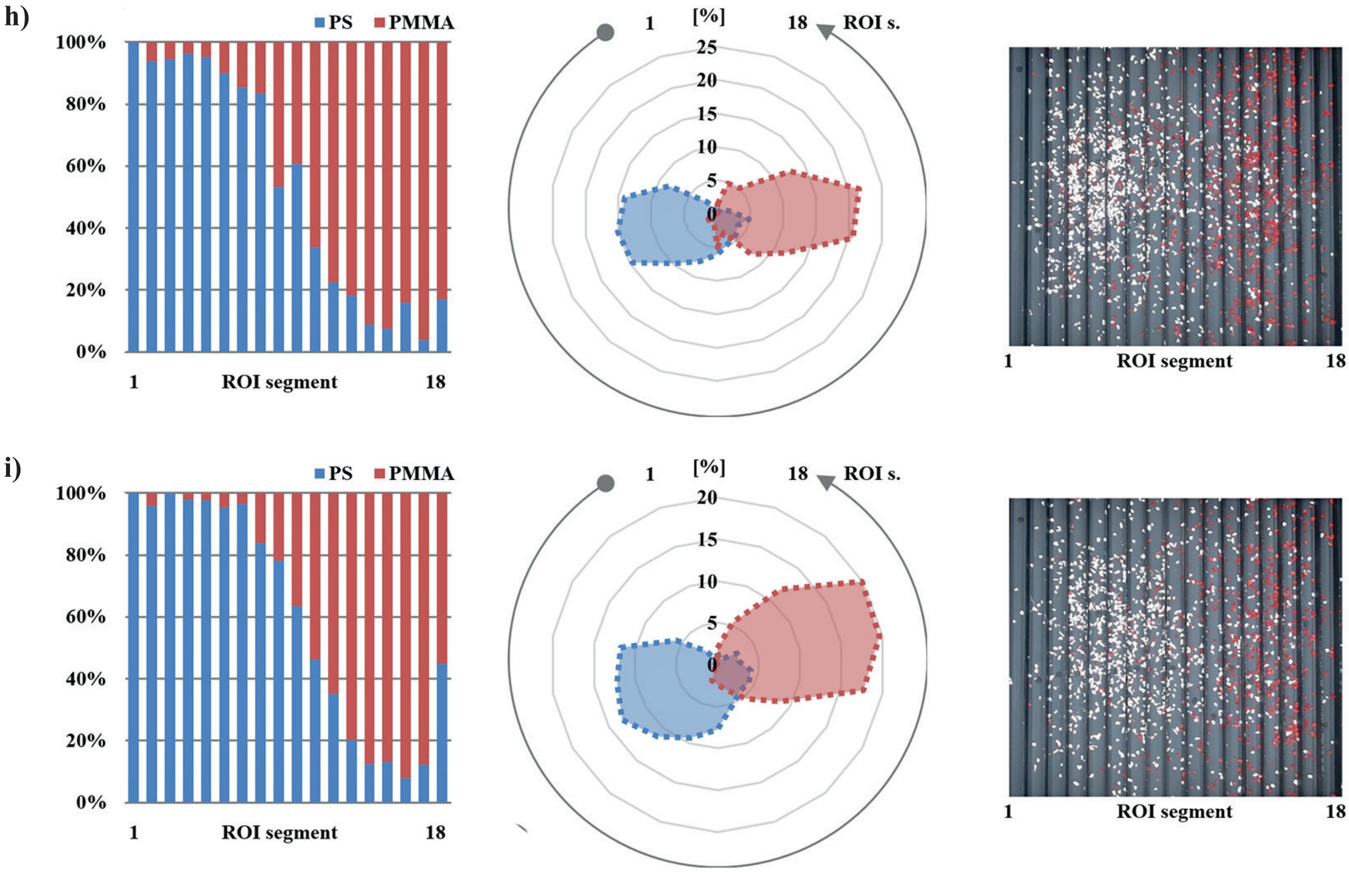

Fig. 9. Results of performed tests for PMMA and PS separation from (a) to (i) correspond to test numbers in Table 1

5. Conclusions and future work

The paper presents and discusses an innovative design of an automated test stand developed by the authors for the purposes of the research on electrostatic separation of plastic waste. The design of the proposed system is based on literature studies as well as on carried out numerical simulations employing the FEM. In order to provide the ability to effectively test the impact of various parameters affecting the electrostatic separation process, the designed test stand has been equipped with an in-house developed computer vision system suited for analyses of the impact of process parameters on the separation efficiency of mixed plastic waste. The application of the proposed vision system provides an innovative method for quick assessment of the quality of such separation. This evaluation is based on the proposed coefficient of the separation effectiveness *SE*.

The prototype of the designed test stand has been built and commissioned. The preliminary studies of the separation process performed on a mixture of PMMA and PS were conducted to demonstrate the high research potential of the developed ES test stand. The conducted research focused on the evaluation of the impact of the corona electrode position and the value of the applied voltage on separation effectiveness, confirmed the ability to determine the optimal values of the studied parameters in terms of separation effectiveness. The research on the development of effective electrostatic separation techniques for plastic mixtures using the developed test stand is ongoing and will be the scope of further scientific publications of the authors.

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