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ELECTROSTATIC SEPARATION OF PET/PVC MIXTURE

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Preliminary notes

Nowadays, due to their numerous favorable properties, plastic materials replace other materials in many industries, especially packaging industry, therefore the generation of plastic waste is constantly increasing. Waste plastics can be recycled, which decreases potential harmful influence on the environment and saves landfill space and natural resources. The aim of the research presented in this paper was to evaluate the performance of the electrostatic separator when separating a PET/PVC mixture. The effect of electrode potential and rotor speed on separation efficiency was studied on three different particle size classes (4/3,15 mm, 3,15/2 mm and 2/1 mm). Indicators of separation efficiency for two-component plastic mixture were the concentrate grade and recovery. The best result (100 % grade and 87 % recovery) was obtained by separating coarse particle size class 4/3,15 mm after two separation stages at the electrode potential of 15,5 kV and rotor speed of 35 m/min.

Keywords: *electrostatic separation, PET, PVC, recycling*

Elektrostatička separacija PET/PVC smjese

Prethodno priopćenje

U današnje vrijeme plastika zamjenjuje druge materijale u mnogim industrijskim granama, pogotovo u proizvodnji ambalaže, zbog čega je i količina otpadne plastike u stalnom porastu. Otpadna plastika može se reciklirati čime se smanjuje prostor potreban za odlagalište i potencijalno štetan utjecaj na okoliš, te ujedno štede prirodni resursi. U radu su prikazani rezultati ispitivanja mogućnosti separacije PET/PVC smjese u elektrostatičkom separatoru. Utjecaj napona elektrode i brzine vrtnje bubnja na učinak separacije ispitivan je na uzorcima različitih klasa veličine zrna (4/3,15 mm, 3,15/2 mm and 2/1 mm). Kao pokazatelji učinkovitosti separacije dvokomponente smjese utvrđivani su kvaliteta koncentrata i iskorištenje korisne komponente. Najbolji rezultati (kvaliteta koncentrata 100 % i iskorištenje 87 %) postignuti su separiranjem klase 4/3,15 mm nakon dva radna stupnja separacije pri naponu elektrode od 15,5 kV i brzini bubnja od 35 m/min.

Ključne riječi: *elektrostatička separacija, PET, PVC, recikliranje*

1 Introduction
Uvod

Plastic materials are increasingly replacing other materials such as metals, glass, ceramics, wood and paper in various products, especially in packaging. Packaging accounts for 35 % of all plastics consumed worldwide [1]. The total global production of plastics grew from around 1,5 million tons in 1950 to 230 million tons in 2009 [2]. Plastics production in Europe (EU27 + Norway and Switzerland) represents 25 % of the global plastics production, with approximately 60 million tons per year. As seen in Fig. 1a, the packaging industry remains the biggest plastics end-user at ca. 40 %, followed by the building and construction sector at 20 %, automotive industry 7 %, electrical and electronics industry 6 %, agriculture, medical, leisure and other applications 27 % [2, 3]. Average annual production of plastic products in the Republic of Croatia was approximately 102 000 tons in the last five years [4]. The major applications of plastics besides packaging include: profile, pipe and sheet production, and building sector (Fig. 1b).

On the other hand, the incessant increase in the consumption of plastic products inevitably results in the generation of a vast solid waste stream that needs to be properly managed to avoid environmental damage. E.g., the total amount of around 24,6 million tons of plastic waste was generated in Europe in 2007 and, on average across the EU, almost two-thirds of that came from the packaging industry [5]. Plastics waste has become one of the larger categories in municipal solid waste (MSW), particularly in the industrialized countries [6, 7]. Croatia is also faced with a similar situation. Plastics account for approximately 11 % of MSW by weight, however, for more than 30 % of MSW by volume (because of the low density of post-consumer plastic waste), about 40 % of which are estimated to be PET packaging [8, 9]. Such large quantities of the diverse mixture of plastics place a great burden on limited landfill capacity and environment without considering an appropriate waste management strategy.

Although waste disposal is the least desirable waste management option due to the increasing waste volume and decreasing landfill disposal capacity, as well as a long decomposition time of plastic materials and emissions of hazardous substances either by weathering, natural drying or incineration processes, a major portion of plastic waste is still either disposed to landfills or incinerated (without energy recovery) and the rest is recycled/reused [10, 11]. Environmental hazards are associated with traditional methods of waste disposal including incineration without energy recovery and landfilling. The incineration of some plastics may cause the emission of large amounts of toxic gases, together with the generation of toxic fly and bottom ash that contain lead and cadmium [12, 13, 14]. Particularly, waste plastics containing PVC lead to air pollution and shorten the life of incinerator as generating many hazardous substances such as hydrogen chloride gas (HCl) and dioxins containing chlorine [6, 15]. In view of these considerations, as well as the rising prices of fossil fuels (as the raw material in plastics production) and the need for limiting greenhouse gases emissions, recycling is rapidly gaining importance as an alternative solution to manage plastic waste [7, 11].

Each subsequent step in the recycling process (collection, sorting and separation, reprocessing of polymers and manufacturing of new products from the melted plastic) adds value to the post-consumer plastics and puts it into marketable form for other processors and end-users that will use them to manufacture new products.

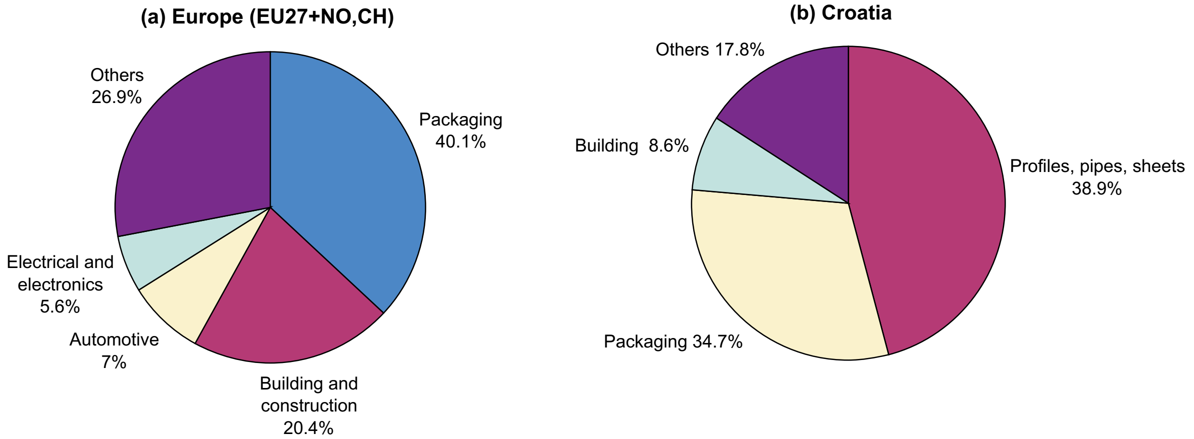

Figure 1 *End-use applications of plastics processed in: (a) Europe and (b) Croatia in 2009* [4]
Slika 1. *Područja primjene plastičnih proizvoda proizvedenih u: (a) Europi i (b) Hrvatskoj u 2009.* [4]

The amount and type of sorting and processing required depends on the purity level to which plastic flakes are processed i.e. the end-use applications they are intended for [16]. Of course, there are many problems facing the plastics recycling industry but they are primarily in the areas of separation and purification. The major problem is connected with a great incompatibility of different polymers present in the waste and with inferior mechanical properties of the products resulting from the processing of such a mixture of polymers. For instance, most packaging plastics are mutually incompatible, and PVC and PET present the worst of the cross-contamination problems [17, 18, 19, 20]. Although post-consumer PET is contaminated with many substances, causing deterioration of its physical and chemical properties during reprocessing, such as acid producing contaminants (polyvinyl acetate, adhesives, PVC), colouring contaminants (e.g. fragments of coloured bottles), water, acetaldehyde, etc., the primary contaminant to the PET recycling process is any source of PVC [16, 21]. PET and PVC have different melting points and thermal stabilities and must not be remelted together. PET melts at ca. 260 °C, while PVC will degrade at cca. 200 °C releasing hydrochloric acid that destroys the desirable properties of PET, causing it to turn yellow and brittle. At the PET melting temperature the PVC will burn and char. Burnt PVC creates black flecks in the otherwise clear PET material, making it unusable for many end-use applications. Furthermore, it can seriously damage the processing equipment. Even a very low concentration of PVC (as low as 100 ppm) in a melt of PET during reprocessing can induce degradation and discoloration, and substantially decrease the quality of the whole batch [20, 22, 23]. Therefore, the removal of contaminants i.e. the separation of different polymers by type in order to get a valuable plastic product is a vital step in the mechanical recycling process of plastics. Accordingly, attempts have been made to develop practical methods for separating mixed plastics.

Although several separation technologies based on the difference in physical or chemical properties of the plastics being separated, including automatic sorting, gravity separation, froth flotation and electrostatic separation, can be applied to efficiently separate mixed plastics waste, they generally have their limitations [7]. Automated sorting systems based on X-ray detection (X-ray transmission and X-ray fluorescence), near infrared (NIR) spectroscopy (sorting by resin type) or optical sorting (sorting by colour) are expensive and their efficiency is limited by the deviation of the process feed characteristics, such as size, shape and surface contamination of plastics object, from predetermined ones [24, 25]. Gravity separation methods are effective for separating materials of different specific gravity (e.g. PVC and PP), but polymers of similar specific gravity (e.g. PVC and PET) cannot be separated using these methods [17, 22]. Froth flotation utilizes the differences in surface properties of particles of various materials and can be effectively used for separating different mixtures of plastics [7, 17, 19, 23, 26, 27, 28]. However, froth flotation as well as wet gravity separation encounters problems such as: treatment of wastewater, requirement for expensive wetting reagents and chemical pretreatment of plastics, and dewatering (drying) the mixture after separation [14]. Electrostatic separation utilizes the differences in electric conductivity, friction charge and dielectric properties between the components in a particulate mixture [29, 30]. Although this separation method has its limitations, it should be taken into consideration, especially in arid areas. Being a dry method, electrostatic separation has a clear advantage over wet methods because of avoiding wastewater generation and dewatering the material after separation, less energy consumption, less equipment corrosion and low operation and amortization costs [31, 32]. A more detailed description of the operating principle of high-tension separator used in this study is given in section 2.2.

The main purpose of the study presented in this paper was to evaluate the separation performance of the high-tension electrostatic separator when separating a PET/PVC mixture. The study was focused on estimating the influence of process variables - electrode potential and rotor speed on the separation efficiency, with the concentrate grade and recovery defined as the indicators of separation efficiency.

2 Experimental
Eksperimentalni dio

2.1 Materials and procedure
Materijali i procedura

The samples used in this study were polyethylene terephthalate (PET bottles) and polyvinyl chloride (PVC pipes) collected from household waste. The samples were shredded in a cutting mill SM 2000, provided by Retsch GmbH (Germany) and then a representative fraction of the plastics was sieved on testing sieves with mesh sizes 4,0 mm, 3,15 mm, 2,0 mm and 1,0 mm. The experiments were

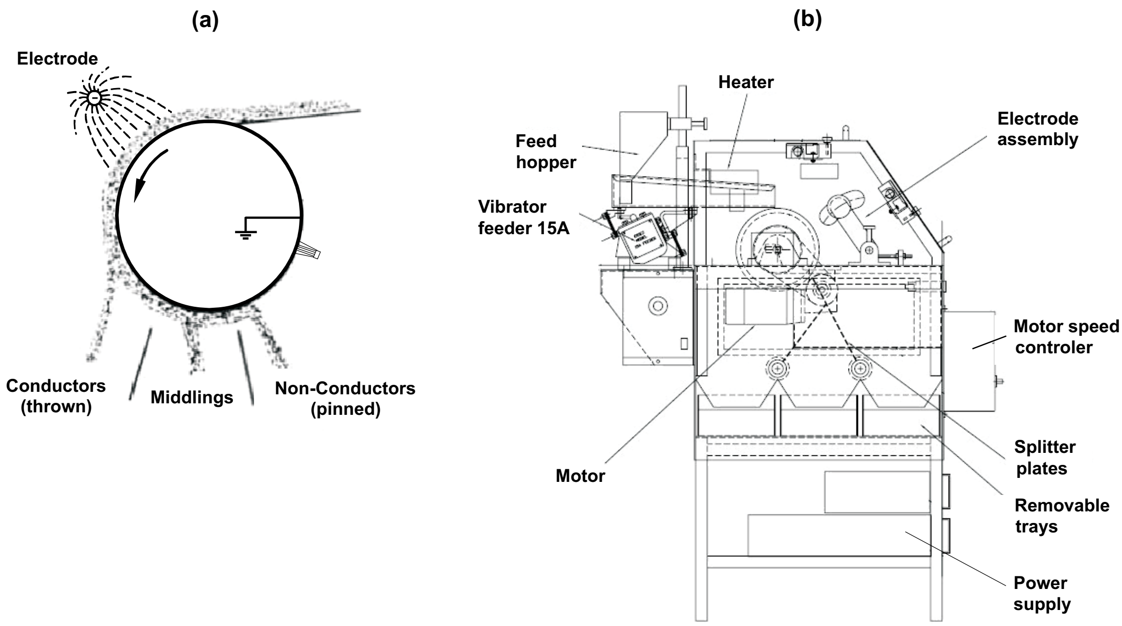

Figure 2 *Laboratory high-tension electrostatic separator Eriez HT 150: (a) operating principle and (b) outline* [35]
Slika 2. *Laboratorijski elektrostatički (korona-) separator Eriez HT 150: (a) princip rada i (b) shematski prikaz* [35]

carried out using 50/50 % artificial mixture of PET and PVC plastics in all three particle size classes (4,0/3,15 mm, 3,15/2,0 mm and 2,0/1,0 mm). Based on preliminary test results [33], it was decided to perform separation tests at the electrode potential ranging from 14,5 kV to 17,5 kV and rotor speed from 35 m/min to 52 m/min. After separation in electrostatic separator, the difference in color between PET (green) and PVC (gray) allowed easy hand-sorting and visual analysis of the separated products (concentrate and gangue). Bottle caps were not included in testing because they are made of polyethylene (PE).

2.2 Separation method
Separacijski postupak

The PVC/PET samples were separated on the basis of differences in surface conductivity, using a high-tension electrostatic separator. The material to be separated is fed on to the earthed rotating roll and subjected to corona discharge from a fine wire electrode (high-tension electrode). A radiant heater is mounted above feed tray to remove moisture from the material. When high voltage is applied to the electrode, the air in the vicinity of the wire electrode is ionized and charged air molecules (positive if the wire is negative, negative if the wire is positive) travel to the rotor, where they strike the particles. Particles with good surface conducting properties ("conductors") lose the charge gained from the air molecules in milliseconds and are "thrown" from the rotor by centrifugal force. Particles with poor surface conducting properties ("non-conductors") retain the charge gained from the air molecules. This retained charge induces an equal, opposite "image" charge inside the rotor and thus non-conducting particles are held or "pinned" to the rotor by these image charges until dislodged by the discharge brush (Fig. 2a). Variation of voltage, rotor speed, splitter position, electrode position and polarity all influence the degree of separation, and only through testing can the optimum settings for different material be established [31, 34, 35]. Fig. 2b shows the outline of laboratory high-tension electrostatic separator (type HT 150 provided by Eriez) used in tests.

2.3 Evaluation of separation efficiency
Vrednovanje učinkovitosti separacijskog postupka

The aim of separation process is to collect valuable component in the concentrate and non-valuable in the gangue. Besides containing valuable component (PET), the concentrate usually also contains non-valuable component (PVC), as well as the gangue, besides non-valuable component, also contains valuable component. Sometimes, the middlings are separated in the process as a third component, which is re-treated. In conducted tests, samples were separated into two products - concentrate and gangue (no middling product; splitter plates closed together), considering PVC particles as non-valuable component since even small PVC content in the mixture causes degradation of PET properties. The separated products were weighed at the end of each test. Indicators of separation efficiency were the concentrate grade and recovery.

Recovery refers to the percentage of valuable component (PET) contained in the feed material that was collected in the concentrate [36]:

$$R = \frac{C \cdot c}{F \cdot f} \cdot 100, \tag{1}$$

where:
R – recovery, %
C – mass of the concentrate, g
c – mass content of PET in the concentrate, %
F – mass of the feed, g
f – mass content of PET in the feed material, %.

The concentrate grade is the percentage of valuable component (PET) in the concentrate:

$$G = \frac{C_{\mathrm{PET}}}{C} \cdot 100, \tag{2}$$

where:
G – concentrate grade, %
C_{PET} – mass of PET in the concentrate, g
C – mass of the concentrate, g.

3
Results and discussion
Rezultati i rasprava

The results of electrostatic separation tests are shown in Figs. 3-9. In the first series of tests (Figs. 3-5), three particle size classes were tested (4/3,15 mm; 3,15/2 mm; 2/1 mm) and the electrode potential ranged from 14,5 to 17,5 kV. Other operating variables were kept constant at the following values: 5 cm distance of the ionizing electrode from the rotor and 35 m/min rotor speed.

Fig. 3 shows that the PET recovery generally increases as the electrode potential increases. The lower values of PET recovery (60 % and 58,33 %) were obtained at the lower values of the electrode potential (14,5 kV to 15 kV), and the highest recovery (74,33 %) at the highest electrode potential (17,5 kV). It is important to note that the electrode potential higher than 17,5 kV results in the rejection of both PET and PVC particles from the rotor. Regarding concentrate grade, PET content increases with the electrode potential up to 100 % (there is no PVC particles in the concentrate). The highest concentrate grade (100 %) is achieved at the potential of 15,5 kV. Further increase of electrode potential results in decrease of concentrate grade and between 16,5 kV and 17,5 kV it is more or less unchangeable, amounting to about 87 %.

Fig. 4 shows the results of separation tests with particle size class 3,15/2 mm. It can be seen that PET recovery increases steeply with increasing electrode potential up to 15 kV. With increasing electrode potential from 15 kV to 16,5 kV, recovery increases slightly (up to about 73 %) and by further increase up to 17,5 kV, it changes insignificantly. Concentrate grade varies from 86 % to 90 % with changes in electrode potential from 14,5 kV to 16,5 kV. Further increase of electrode potential up to the maximum value of 17,5 kV reduces concentrate grade to the lowest value of 69,21%.

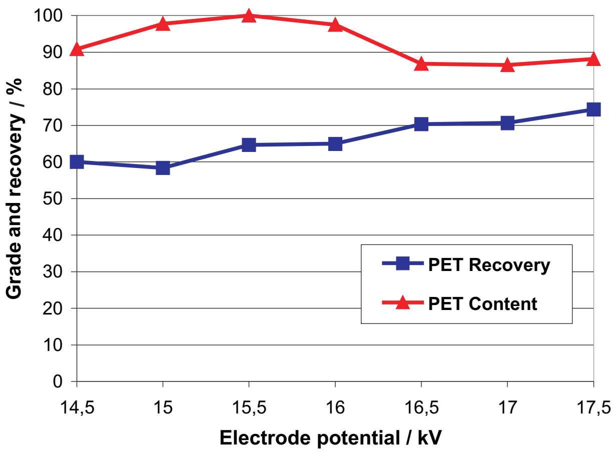

***Figure 3** Effect of electrode potential on the separation of PET/PVC mixture; particle size class 4/3,15 mm*
***Slika 3.** Utjecaj napona elektrode na uspješnost separacije PET/PVC smjese, klase 4/3,15 mm*

Fig. 5 shows the results obtained by testing particle size class 2/1 mm. With increasing electrode potential, PET recovery increases steeply up to 69 % at the electrode potential of 15,5 kV, then fluctuates from 69 % to 73 %, and again increases but to a lesser extent at electrode potential higher than 16,5 kV. Regarding PET content, it can be generally said that it decreases with increasing electrode potential, from a maximum of 84,21 % (14,5 kV) to a minimum of 62,08 % (17,0 kV).

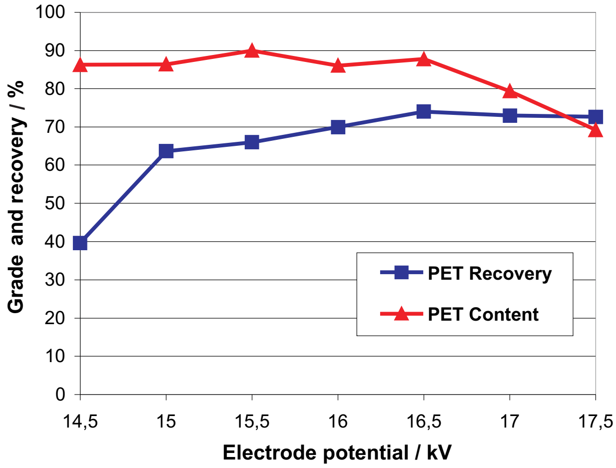

***Figure 4** Effect of electrode potential on the separation of PET/PVC mixture; particle size class 3,15/2 mm*
***Slika 4.** Utjecaj napona elektrode na uspješnost separacije PET/PVC smjese, klase 3,15/2 mm*

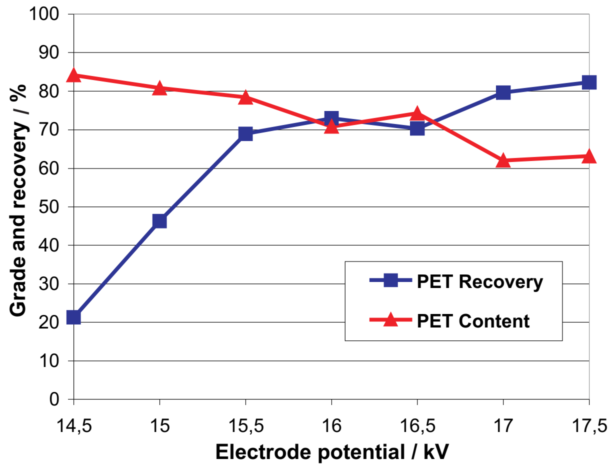

***Figure 5** Effect of electrode potential on the separation of PET/PVC mixture; particle size class 2/1 mm*
***Slika 5.** Utjecaj napona elektrode na uspješnost separacije PET/PVC smjese, klase 2/1 mm*

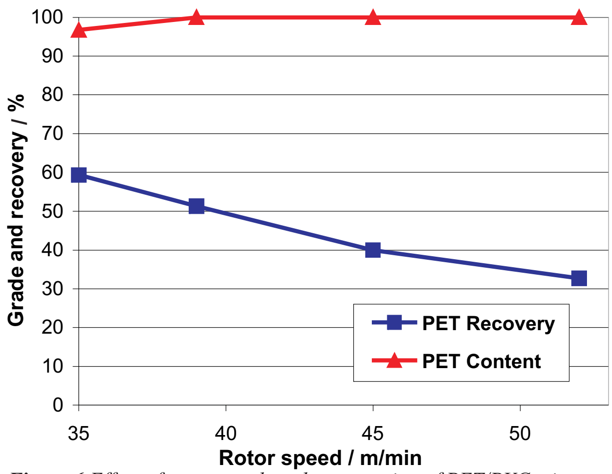

***Figure 6** Effect of rotor speed on the separation of PET/PVC mixture; particle size class 4/3,15 mm*
***Slika 6.** Utjecaj brzine rotora na uspješnost separacije PET/PVC smjese, klase 4/3,15 mm*

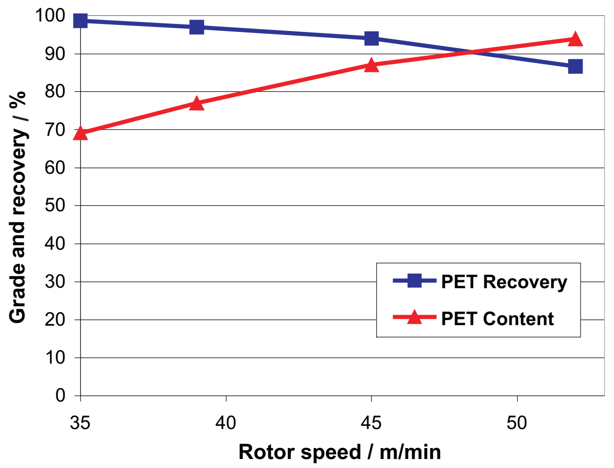

Figure 7 *Effect of rotor speed on the separation of PET/PVC mixture; particle size class 3,15/2 mm*
Slika 7. *Utjecaj brzine rotora na uspješnost separacije PET/PVC smjese, klase 3,15/2 mm*

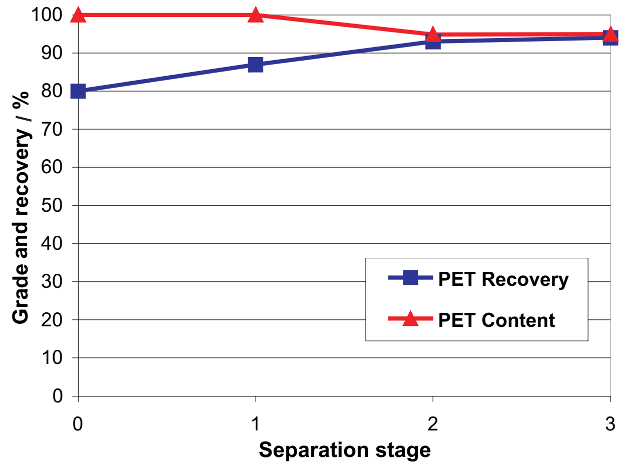

Figure 9 *Effect of processing stage on the separation of PET/PVC mixture; particle size class 4/3,15 mm*
Slika 9. *Utjecaj broja radnih stupnjeva na uspješnost separacije PET/PVC smjese, klase 4/3,15 mm*

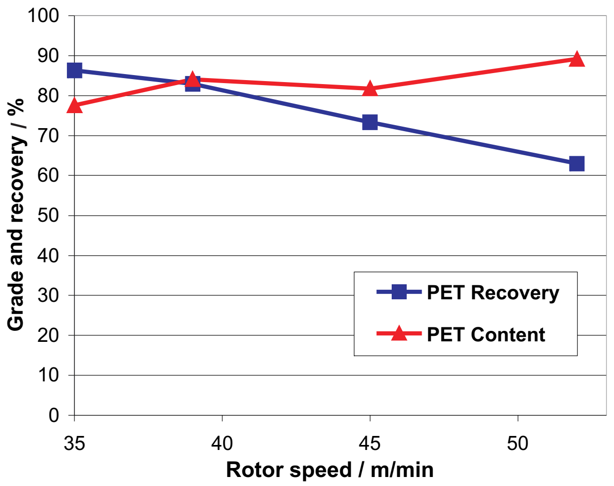

Figure 8 *Effect of rotor speed on the separation of PET/PVC mixture; particle size class 2/1 mm*
Slika 8. *Utjecaj brzine rotora na uspješnost separacije PET/PVC smjese, klase 2/1 mm*

Figs. 6-8 show the results of the second series of tests. As in the first series, the same three particle size classes were tested. The rotor speed was variable and ranged from 35 to 52 m/min. In the first series, the highest PET content in the concentrate (100 %) was obtained at the electrode potential of 15,5 kV, therefore it was decided to perform the next test with coarse particle size (class 4/3,15 mm) at this potential and the same distance of ionizing electrode from the rotor (5 cm). From the results shown in Fig. 6, it can be seen that recovery decreases with increasing rotor speed. PET content in the concentrate was 100 %, except in the first test (96,74 %) at the rotor speed of 35 m/min.

Since in the first series of tests with particle size classes 3,15/2 mm and 2/1 mm the concentrate grade of 100 % was not achieved, the second series of tests with those classes was performed at a maximum electrode potential of 17,5 kV enabling the highest PET recovery, and at the same distance of electrode from the rotor (5 cm). Test results obtained with each particle size class are shown in Fig. 7 and Fig. 8. In both cases, recovery decreases with increasing rotor speed and PET content in the concentrate is the highest at maximum rotor speed (93,86 % obtained by testing size class 3,15/2 mm and 89,15 % by testing size class 2/1 mm).

After the above-described series of tests it was decided to conduct a multi-stage separation test with the aim to determine the number of stages required to achieve high recovery and, if it is possible, to retain 100 % PET content in the concentrate. The results of this test are shown in Fig. 9. As shown, PET recovery was 80 % after rough separation stage, and increased from 80 % to 87 % after first separation stage, while concentrate grade remained unchanged at the value of 100 %. After second separation stage, recovery increased to 93 % but at the same time concentrate grade decreased from 100 % to 94,9 %. Finally, after third separation stage, recovery increased slightly from 93 % to 94 % as well as concentrate grade from 94,90 % to 94,95 %.

4
Conclusion
Zaključak

The objective of the conducted tests was to evaluate the separation efficiency of the high-tension electrostatic separator when separating a PET/PVC mixture. The effects of electrode potential and rotor speed on the separation efficiency were studied on three different particle sizes (4/3,15mm, 3,15/2 and 2/1 mm). The results of conducted tests show that separation is dependent on electrode potential and rotor speed. Generally, with increasing electrode potential, recovery will also increase. Rotor speed increase will cause a recovery decrease and concentrate grade increase. Regarding particle size, it could be concluded that the separability decreases with decreasing particle size. PET content in the concentrate and recovery could be improved by multi-stage separation. The best result was obtained by separating coarse particle size class 4/3,15 mm at the electrode potential of 15,5 kV and rotor speed of 35 m/min after two separation stages, because PET content was still 100 % and recovery 87 %. Further testing should include determination of interaction effects between all variables by using experimental design.

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5
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