Electrostatic separation of binary mixtures of some biodegradable polymers and poly(vinyl chloride) or poly(ethylene terephthalate)

Marian Żenkiewicz[1), *)], Tomasz Żuk[2)], Jacek Pietraszek[3)], Piotr Rytlewski[1)], Krzysztof Moraczewski[1)], Magdalena Stepczyńska[1)]

DOI: dx.doi.org/10.14314/polimery.2016.835

Abstract: There are presented results of investigation of electrostatic separation of binary mixtures containing a biodegradable polymer {polylactide (PLA), polycaprolactone (PCL), or poly(3-hydroxybutyrate-*co*-4-hydroxybutyrate) [P(3,4HB)]} and a commonly used polymer [poly(vinyl chloride) (PVC) or poly(ethylene terephthalate) (PET)]. It was found that the binary mixtures of these polymers could be efficiently separated. The electrostatic separation process of the P(3,4HB)/PET mixture appeared to be most successful. It is indicated that the share of a biodegradable component in the mixture essentially influences the separation effects. Therefore, suitable choice of necessary conditions is needed to perform the separation process, which includes appropriate separator settings, depending on fractions of individual components in the mixture being separated.

Keywords: electrostatic separation, binary mixtures, biodegradable polymers, PVC, PET.

Separacja elektrostatyczna dwuskładnikowych mieszanin wybranych polimerów biodegradowalnych i poli(chlorku winylu) lub poli(tereftalanu etylenu)

Streszczenie: W artykule przedstawiono wyniki badań procesu separacji elektrostatycznej mieszanin dwuskładnikowych zawierających polimery biodegradowalne {polilaktyd (PLA), polikaprolakton (PCL) lub poli(3-hydroksymaślan-*co*-4-hydroksymaślan) [P(3,4HB)]} i polimery powszechnego użytku [poli(chlorek winylu) (PVC) lub poli(tereftalan etylenu) (PET)]. Stwierdzono, że mieszaniny tych polimerów mogą być skutecznie rozdzielane w tym procesie. Najbardziej efektywna okazała się separacja mieszaniny P(3,4HB)/PET. Z badań wynika również, że najistotniejszym czynnikiem wpływającym na skuteczność tej separacji jest udział masowy składnika biodegradowalnego w danej mieszaninie. Z tych względów wymagany jest odpowiedni dobór warunków prowadzenia separacji elektrostatycznej, w tym nastaw separatora w zależności od udziału poszczególnych składników mieszaniny rozdzielanej.

Słowa kluczowe: separacja elektrostatyczna, mieszaniny dwuskładnikowe, polimery biodegradowalne, PVC, PET.

Rapidly growing production of polymeric materials causes significant rise of plastic waste being a large environmental pollution source. This implies a necessity to develop recycling technologies, including mechanical recycling that involves many unit operations, among which sorting plays a key role. The sorting consists in isolating of individual polymers from the waste, following removal of impurities [1–4]. The electrostatic sorting, or the electrostatic separation, has become a subject of many studies. The results obtained so far prove usability, small environmental pollution load, and economic effectiveness of that method, utilized in mechanical recycling of the waste that contains commonly used polymers [5–7].

Electrical charging of particles in a mixture being separated is an essential part of the electrostatic separation, which determines effects of this process. Mechanical triboelectric charging is a method applied most often. The tribocharging occurs here due to both the mutual friction of the mixture particles moving in a tribocharger and the friction of the particles against the tribocharger walls [8–11]. Fluidized-bed triboelectric charging is another widely

---

[1)] Kazimierz Wielki University, Department of Materials Engineering, Chodkiewicza 30, 85-064 Bydgoszcz, Poland.

[2)] Institute for Engineering of Polymer Materials and Dyes, M. Skłodowskiej-Curie 55, 87-100 Toruń, Poland.

[3)] Cracow University of Technology, Institute of Applied Informatics, Jana Pawla II 37, 31-864 Kraków, Poland.

[*)] Author for correspondence; e-mail: marzenk@ukw.edu.pl

used technique, in which the friction between the polymer particles occurs in a fluidized moving bed [12, 13]. The tribocharging effects depend here on the conditions under which this process is carried out, *e.g.*, duration of the tribocharging process and humidity of the surrounding air, as well as on types of polymers being tribocharged and their positions in the triboelectric series [5, 6, 11, 14–16].

In the recent twenty years, a growing interest in the biodegradable polymers, especially such as polylactide (PLA), polycaprolactone (PCL), and polyhydroxyalkanoates (PHA), has been observed. From PHA, poly(3-hydroxybutyrate) (P3HB) and its copolymers like poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV) and poly(3-hydroxybutyrate-*co*-4-hydroxybutyrate) [P(3,4HB)] are of special importance [17–24]. This interest was mostly caused due to the fact that these polymers easily undergo biodegradation under conditions of industrial composting, thus, they do not cause large environmental load [25, 26], which obviously limits interest in recycling of these polymers. However, as it is evident from recently published relevant results, PLA, PCL, and P(3,4HB) can be multiprocessed with no significant deterioration of their physical properties [27–29]. Therefore, it may be assumed that the mechanical recycling of the waste containing the above-mentioned polymers can be an important method for the waste management, constituting an alternative to the industrial composting. Therefore, the electrostatic separation of mixtures containing PLA, PCL, or P(3,4HB) may become a subject of interest for science and industry. By now, there is no information in the available literature on the results of studies on the electrostatic separation of mixtures composed of these polymers or mixtures of these polymers with commonly used polymers, such as poly(vinyl chloride) (PVC) and poly(ethylene terephthalate) (PET).

The aim of the present work was to determine experimentally a possibility of the electrostatic separation of binary mixtures containing a biodegradable polymer [PLA, PCL, or P(3,4HB)] and commonly used polymer (PVC or PET). The choice of these polymers was justified by their significance in practice and the ability to be multiprocessed [27–29]. The latter feature enables reuse of these polymers' waste as a product of the mechanical recycling. Therefore, the electrostatic separation of mixtures of these polymers can be an advantageous technique due to practical reasons.

EXPERIMENTAL PART

Materials

Biodegradable polymers:

– Polylactide (PLA), of type 2002D (NatureWorks®, USA), density (*d*) equal 1.27 g/cm^3, containing 96.5 and 3.5 % of monomeric units L and D, respectively.

– Poly(ε-caprolactone) (PCL), of type Capa FB100 (Perstorp, Sweden), *d* = 1.16 g/cm^3.

– Poly(3-hydroxybutyrate-*co*-4-hydroxybutyrate) [P(3,4HB)], of type SoGreen-2001a (Tianjin GreenBio Materials, China), *d* = 1.24 g/cm^3.

Commonly used polymers:

– Poly(vinyl chloride) (PVC), of type WT-14 (Anwil, Poland), *d* = 1.56 g/cm^3.

– Poly(ethylene terephthalate) (PET), of type SKYPET-BL 8050 (SK Eurochem, Poland), *d* = 1.39 g/cm^3.

Powder dyes:

– GREEN, BLUE, and RED (Evonik Colortrend B.V., Netherlands).

Instruments

The following research instruments were used:

– Co-rotating double-screw extruder, of type BTSK 20/40D (Bühler, Switzerland), used to granulate the studied polymers.

– Laboratory balance, of type PS/600/C/2 (Radwag, Poland), of readability ± 1 · 10^{-3} g, used to weigh the studied samples and their fractions after the electrostatic separation.

– Moisture balance, of type MAX 50/1 (Radwag, Poland), of readability ± 1 · 10^{-4} g, provided with a drying chamber including a halogen lamp, meant for measuring moisture contents in the extruded and granulated polymers.

– Electrostatic drum-type separator (Institute for Engineering of Polymer Materials and Dyes, Toruń, Poland), which has been described elsewhere [30, 31].

Preparation of the samples

The sample preparation procedure included: drying of the PLA, PCL, P(3,4HB), PVC, and PET samples intended for the investigation, dyeing of PLA, PCL, and P(3,4HB), extruding of these polymers in the form of granules, conditioning of the granulated polymers, drying and measuring of moisture contents of the conditioned granulated polymers, and weighing of samples of binary mixtures meant for the electrostatic separation.

Before the extrusion, all the polymers were dried under the conditions specified by the polymer manufacturers, using the laboratory drying oven with forced air circulation. The drying temperature of the particular polymers ranged from 50 to 120 °C while the drying time was 6 h for all of the polymers.

The extrusion of the polymers was performed in order to obtain polymeric granules of various colors and similar sizes and shapes. Because densities of the biodegradable polymers differed little, formation of the granules of similar shapes and sizes was necessary in order to provide similar conditions for the electrostatic separation of the particular mixtures. Various colors of the granules enabled identification of the polymers during the separation. The dyeing and extrusion were carried out using BTSK 20/40D double-srew extruder. The extrusion process was performed without degassing of the samples, at a constant screw rotation speed of 250 min^{-1}. Dyes in the form of granulated concentrates were added in the amounts of 0.5 wt %. The granules were obtained in the form of cylinders of sizes similar to one another ($h \approx 4$ mm, $r \approx 2.7$ mm) and conditioned at constant parameters (T = 23 °C, relative humidity HR = 50.0 %, t = 96 h), according to the relevant standard (PN-EN ISO 291:2010).

Methods of testing

Moisture contents of individual granulated polymers were determined using moisture balance, type MAX 50/1. All the polymers were dried under the same conditions. The drying temperature of 50 °C was assumed while considering the lowest melting point, exhibited by PCL ($T_m \approx$ 50–60 °C). The drying was continued until a constant mass was achieved. A change in the material mass was controlled by relevant software. When the mass change was less than 1 mg in 60 s, then the drying process was automatically terminated. The moisture contents of all the granulated polymers were found to be less than 0.2 wt %.

Six types of the binary mixtures were examined. They were designated with the general symbol of A/B, in which A stands for a biodegradable polymer [PLA, PCL, or P(3,4HB)] and B, for a commonly used polymer (PVC or PET). The specific designations of these mixtures were: PLA/PVC, PLA/PET, PCL/PVC, PCL/PET, P(3,4HB)/PVC, and P(3,4HB)/PET.

Effects of the electrostatic separation depend on many various factors, thus, investigation of this process had to be performed according to the design of experiment theory. Four input variables were assumed to characterize the studied process. These were: (i) mass fraction (x_1) of a component A in the A/B mixture, expressed as the percentage, (ii) tribocharging time (x_2, in seconds), (iii) potential difference (x_3, in kV) between the high-voltage elliptical electrode and earthed cylindrical electrode of the electrostatic separator (at a constant interelectrode gap, it is directly proportional to the electrostatic field intensity in the interelectrode space), and (iv) rotational speed (x_4, in min^{-1}) of the earthed cylindrical electrode of the electrostatic separator. The variables on the output of the process were: (i) purity (y_1) of the component A derived from the A/B mixture, also designated as C_A (in %), being a quotient of mass of the component dominating in a specific fraction and mass of that fraction, (ii) recovery yield (y_2) of the component A, also designated as W_A (in %), being a quotient of mass of the component A dominating in a specific fraction and mass of that component in a sample of the A/B mixture, (iii) purity (y_3) of the component B derived from the A/B mixture, also designated as C_B (in %), (iv) recovery yield (y_4) of the component B, also designated as W_B (in %). Inseparable fractions of the mixtures, being also products of the electrostatic separation, are not discussed in the present work.

While considering the above characteristics of the separation process, the purpose of this investigation, and results of the analysis of literature [32, 33], it had been assumed that the examinations would be performed according to a complete bi-level composite plan, widely applied in the studies of that type. Samples of each mixture (weight of 0.2 kg) were prepared, the compositions of which were as follows (A/B): 20/80, 35/65, 50/50, 65/35, and 80/20 wt % (x_1 = 20, 35, 50, 65, and 80 wt %). The samples were tribocharged in a fluidized moving bed and then separated in an electrostatic separator used in these investigations.

According to the results of our earlier experiments [34–36], the following values of the parameters of the electrostatic separation process were applied: (i) tribocharging time, x_2 = 10, 85, 160, 235, and 310 s, (ii) voltage of the high-voltage elliptical electrode, x_4 = 10, 13, 16, 19, and 22 kV, being equivalent to 2.0, 2.6, 3.2, 3.8, and 4.4 kV/cm, with the constant interelectrode gap of 5 cm, and (iii) rotational speed of the cylindrical electrode, x_3 = 15, 18, 21, 24, and 27 min^{-1}.

A design matrix elaborated and presented in [37] was used in this study. Since six types of the binary mixtures were examined and each mixture consisted of 30 samples, the total number of experiments was 180.

RESULTS AND DISCUSSION

The effects of the separation process (the output variables) are summarized in Tables 1–6 as sets of values of C_A, W_A, C_B, and W_B relating to six binary mixtures (A/B).

The data presented in these Tables indicate that the output variables vary in wide ranges depending on changes in the input variables. Separation of a binary mixture of a biodegradable polymer [PLA, PCL, or P(3,4HB)] and PVC (Tables 1, 3 and 5) results in obtaining the PVC fraction of high purity while the recovery yield of each of the biodegradable polymers is low. The purity of the biodegradable polymer fractions varies and the inequalities $C_{PLA} > 80$ %, $C_{PCL} > 70$ %, and $C_{P(3,4HB)} > 70$ % are obeyed for most of the investigated samples.

Similar separation effects are found for the PLA/PET and PCL/PET mixtures (Tables 2 and 4): the purity of the PET fraction is high whereas the recovery yields of PLA and PCL are low. In the case of the P(3,4HB)/PET mixture, however, the values of $W_{P(3,4HB)}$ and C_{PET} are large (Table 6).

Under conditions of the industrial separation of the plastic waste mixtures, the x_1 variable (the fraction of the component A in the A/B mixture) may vary in an uncontrolled way within a wide range (0–100 wt %) while the x_2, x_3, and x_4 variables are fixed as the separator parameters are set beforehand. The data obtained in this work (Tables 1–6) may be used to establish conditions under which the mixture separation can be carried out in dependence on the mass fractions of individual components. The determination of these conditions consists in suitable choice of the separator parameters, *i.e.*, sets of the x_2, x_3, and x_4 variables, for the fixed x_1 values. Therefore, a criterion for selection (criterion S) of the x_2, x_3, and x_4 values has firstly to be formulated in dependence on the preferred values of the output variables (C_A, W_A, C_B,

Table 1. Effects of separation of the PLA/PVC mixture

Sample no.	C_{PLA}, %	W_{PLA}, %	C_{PVC}, %	W_{PVC}, %
1	91.1	14.3	100.0	83.2
2	97.0	16.2	100.0	93.4
3	99.0	21.0	100.0	98.2
4	100.0	22.7	100.0	98.9
5	89.0	15.5	100.0	76.1
6	89.5	15.9	100.0	84.5
7	97.9	20.3	100.0	93.6
8	98.2	20.3	100.0	95.0
9	70.5	6.4	99.6	60.3
10	74.8	5.4	99.4	63.3
11	92.5	7.4	100.0	91.2
12	91.6	7.3	99.7	88.9
13	69.9	5.1	99.9	64.1
14	65.4	4.2	99.5	61.6
15	88.8	8.0	99.6	86.2
16	91.4	7.2	99.9	89.8
17	89.4	28.0	100.0	74.7
18	46.0	1.7	99.1	63.2
19	88.0	16.6	99.9	82.7
20	94.4	11.4	100.0	92.0
21	81.4	9.2	100.0	43.5
22	99.3	12.9	100.0	98.1
23	90.8	12.0	100.0	89.1
24	94.5	12.9	100.0	90.6
25	89.9	13.8	99.9	86.3
26	94.9	13.1	100.0	85.9
27	92.9	12.4	100.0	86.9
28	89.3	35.4	100.0	88.6
29	92.0	13.2	100.0	87.9
30	92.2	12.5	100.0	87.1

Table 2. Effects of separation of the PLA/PET mixture

Sample no.	C_{PLA}, %	W_{PLA}, %	C_{PET}, %	W_{PET}, %
1	90.8	22.5	100.0	39.9
2	94.0	32.4	100.0	79.2
3	95.3	37.0	100.0	80.0
4	97.3	35.8	100.0	89.9
5	89.5	27.7	100.0	68.1
6	93.8	28.9	100.0	76.3
7	93.7	24.6	100.0	79.0
8	97.9	32.2	100.0	92.0
9	58.7	15.8	99.9	38.1
10	62.8	13.4	99.7	49.2
11	60.7	17.6	100.0	37.6
12	64.3	13.8	99.8	57.0
13	59.5	13.0	99.7	26.6
14	56.8	10.9	100.0	47.8
15	60.3	12.5	99.9	50.6
16	65.9	8.3	99.9	64.9
17	82.5	39.1	100.0	56.8
18	25.3	1.4	99.3	26.7
19	73.8	2.5	100.0	83.6
20	62.0	19.1	100.0	47.1
21	62.2	20.9	100.0	30.4
22	96.0	21.7	100.0	96.5
23	72.5	14.9	100.0	56.5
24	87.6	14.6	100.0	81.2
25	68.7	27.1	100.0	52.6
26	78.9	13.4	100.0	53.6
27	76.0	11.8	100.0	57.2
28	73.9	13.3	100.0	58.4
29	75.6	13.7	100.0	57.1
30	72.1	22.1	100.0	54.4

and W_B). In particular, that criterion may be in the form of (i) a maximum value of one or several output variables or (ii) a maximum value of the sum of several or all of the output variables. The proper separator parameters may be considered as a set of the input variables (x_2, x_3, and x_4) for which the criterion S is fulfilled under conditions of the experiment being performed.

Taking into account these considerations, an analysis of the results of separation of mixtures differing in fractions of particular components (different values of x_1) was performed, using the data of Tables 1–6. The sample sets included in these tables were divided into five disjoint subsets in such a way that the value of x_1 was constant for the samples of each of the subsets. The subsets contained samples of the following numbers: {1 ÷ 8}, {9 ÷ 16}, {17}, {18}, and {19 ÷ 30}. The values of x_1 for these subsets were 35, 65, 20, 80, and 50 wt %, respectively.

In our analysis we assumed that criterion S is fulfilled by such sample of each subset, for which the sum of the values of all the output variables is maximal. Numbers of the samples fulfilling the criterion S are presented in the first column of Table 7.

In other columns of this Table the sums of the output variables of these samples are included. The numbers N

T a b l e 3. Effects of separation of the PCL/PVC mixture

Sample no.	C_{PCL}, %	W_{PCL}, %	C_{PVC}, %	W_{PVC}, %
1	73.3	26.4	100.0	40.6
2	84.5	31.1	100.0	66.7
3	83.6	49.9	100.0	80.1
4	83.9	42.3	100.0	74.9
5	80.6	26.3	99.9	54.2
6	76.9	29.1	99.8	50.6
7	82.5	28.8	99.8	52.2
8	81.1	36.4	99.9	71.7
9	53.9	15.2	97.4	20.1
10	52.2	10.9	97.2	19.3
11	56.8	13.8	96.2	21.8
12	60.1	16.6	98.5	41.1
13	51.7	12.3	96.5	13.8
14	56.2	15.9	96.1	26.8
15	60.9	16.8	98.7	42.7
16	73.4	10.1	98.2	57.1
17	91.9	48.3	100.0	69.9
18	57.0	4.9	86.3	41.1
19	68.7	31.7	100.0	43.5
20	83.5	9.2	99.4	69.3
21	55.0	13.7	100.0	9.5
22	75.3	27.0	98.8	65.0
23	78.5	16.0	99.1	55.1
24	91.3	12.9	98.6	83.2
25	82.0	10.4	98.8	80.3
26	89.3	12.6	99.3	68.0
27	90.7	11.4	99.2	75.7
28	73.4	21.0	98.7	63.2
29	90.6	8.6	98.6	77.6
30	87.2	6.8	97.9	79.4

T a b l e 4. Effects of separation of the PCL/PET mixture

Sample no.	C_{PCL}, %	W_{PCL}, %	C_{PET}, %	W_{PET}, %
1	90.6	15.4	100.0	55.1
2	96.1	20.9	99.9	82.3
3	98.1	24.4	99.8	90.3
4	99.2	30.0	100.0	95.0
5	87.0	18.5	99.8	66.0
6	86.2	15.4	100.0	74.7
7	96.3	27.8	99.9	87.8
8	96.7	27.3	99.9	94.2
9	59.7	17.1	99.3	31.7
10	72.2	11.1	99.7	52.3
11	88.7	16.5	99.7	73.8
12	88.4	17.6	99.7	84.1
13	63.8	11.4	99.5	32.6
14	72.7	12.9	99.2	63.5
15	78.5	18.1	99.0	71.3
16	93.3	6.3	99.4	89.6
17	79.6	12.1	99.8	58.4
18	47.5	3.4	89.8	43.8
19	94.1	25.0	99.9	82.2
20	82.8	9.9	99.1	78.3
21	53.0	10.6	99.9	18.9
22	92.0	15.3	99.3	86.7
23	85.6	10.0	99.5	73.9
24	94.6	11.9	99.2	91.3
25	86.4	18.3	99.8	82.8
26	91.0	11.8	99.5	81.6
27	89.8	12.4	99.0	83.5
28	86.6	15.1	99.6	84.3
29	89.9	14.6	99.5	84.6
30	90.3	13.8	99.2	84.6

(sums of the values in each column of Table 7, divided by 2000 as a product of maximum value (100) of each output variable and 4 output variables and 5 samples of each type mixture; $2000 = 100 \cdot 4 \cdot 5$) presented in the last row of the Table 7 may be regarded as a measure of the separation effectiveness for each type of mixture. The numbers of samples shown in Table 7 enables to select unequivocally the x_2, x_3, and x_4 values fulfilling the accepted criterion *S*.

While combining the data of Tables 1–7, plots of the values of the output variables of the studied mixtures were drawn as functions of the compositions of these mixtures (Figs. 1–6).

These diagrams show what the separation effects can be obtained by using the applied separator, while choosing its parameters according to the above-defined criterion *S*. The plots shown in Figs. 1–6 indicate that:

1. Purity of the PVC and PET fractions, derived from the mixtures containing PLA or P(3,4HB), is very high within the whole ranges of compositions of these mixtures, *i.e.*, it is higher than 99.1 wt %. Purity of these fractions derived from the mixtures containing up to 65 wt % of PCL is also high (higher than 98.2 and 99.7 wt %, respectively). In the case of the mixture containing 80 wt %

Table 5. Effects of separation of the P(3,4HB)/PVC mixture

Sample no.	$C_{P(3,4HB)}$, %	$W_{P(3,4HB)}$, %	C_{PVC}, %	W_{PVC}, %
1	87.1	34.7	100.0	32.2
2	84.3	37.3	100.0	48.0
3	89.5	39.0	100.0	59.7
4	93.7	39.5	100.0	70.7
5	85.1	39.1	100.0	47.8
6	90.5	35.6	100.0	56.6
7	91.5	41.3	100.0	57.2
8	95.9	46.0	100.0	88.1
9	68.1	5.9	100.0	36.8
10	53.5	2.5	99.9	28.6
11	48.0	1.5	100.0	39.3
12	68.2	4.2	100.0	55.6
13	56.7	1.1	100.0	43.4
14	42.5	1.0	100.0	52.1
15	67.0	2.4	100.0	67.8
16	79.2	3.3	100.0	64.4
17	85.1	47.8	100.0	34.7
18	0.0	0.0	99.9	54.9
19	71.9	12.9	100.0	33.3
20	73.4	13.8	99.9	37.1
21	62.4	15.3	100.0	17.9
22	84.4	19.2	99.9	73.1
23	69.9	18.8	100.0	38.1
24	79.8	14.9	99.9	56.9
25	70.3	22.0	100.0	41.2
26	74.9	13.4	100.0	36.9
27	74.0	17.4	100.0	43.1
28	64.1	20.2	100.0	36.8
29	75.7	16.1	100.0	46.6
30	70.9	18.8	100.0	38.5

Table 6. Effects of separation of the P(3,4HB)/PET mixture

Sample no.	$C_{P(3,4HB)}$, %	$W_{P(3,4HB)}$, %	C_{PET}, %	W_{PET}, %
1	46.1	100.0	99.9	37.2
2	56.8	100.0	100.0	59.0
3	86.6	100.0	100.0	91.7
4	90.5	100.0	100.0	94.4
5	37.3	100.0	99.8	9.5
6	38.2	100.0	100.0	12.8
7	48.4	100.0	100.0	42.6
8	60.8	100.0	100.0	65.3
9	93.4	100.0	100.0	86.8
10	96.9	100.0	100.0	94.0
11	99.9	100.0	100.0	99.8
12	99.7	100.0	100.0	99.5
13	66.7	100.0	100.0	7.2
14	70.3	100.0	99.8	21.5
15	83.1	100.0	99.9	62.2
16	97.1	99.5	99.1	94.5
17	25.2	100.0	100.0	25.6
18	99.1	100.0	100.0	96.2
19	90.3	100.0	100.0	89.3
20	55.8	100.0	100.0	20.8
21	51.3	100.0	100.0	5.0
22	92.7	100.0	99.9	92.2
23	69.6	100.0	100.0	56.3
24	91.6	100.0	100.0	90.8
25	86.3	100.0	100.0	84.1
26	80.8	100.0	100.0	76.3
27	82.8	100.0	100.0	79.2
28	83.5	100.0	100.0	80.2
29	82.6	100.0	100.0	78.9
30	81.9	100.0	100.0	77.8

of PCL, the purity of the fractions is somewhat lower (86.3 and 89.8 wt %, respectively).

2. Purity of the fractions of the biodegradable polymers [PLA, PCL, and P(3,4HB)] and recovery yield of commonly used polymers (PVC and PET) essentially depend on composition of the mixtures and vary similarly to one another. These quantities reach values higher than 80 wt % when the fractions of a biodegradable polymer are 35–65 wt % in PLA/PVC and PCL/PET mixtures and 35–50 wt % in PLA/PET and PCL/PVC mixtures. In the case of P(3,4HB)/PVC mixtures, $C_{P(3,4HB)}$ is not less than 80 wt % if the fractions of P(3,4HB) are 20–65 wt %, while W_{PVC} is higher than 80 wt % only when the fraction of P(3,4HB) is 35 wt %. Better results are observed for the P(3,4HB)/PET mixtures in the case of which $C_{P(3,4HB)}$ and W_{PET} reach the values higher than 90 wt % if the fractions of P(3,4HB) are 35–80 wt %.

3. The recovery yield of the biodegradable polymers, relating to the studied mixtures except for P(3,4HB)/PET), is less than 50 wt % and rapidly decreases when the fraction of a relevant biodegradable polymer increases. However, the recovery yield of P(3,4HB), from the P(3,4HB)/PET mixtures, is very high within the whole range of fractions of P(3,4HB) ($W_{P(3,4HB)} \geq 99.9$ wt %). According to the results pre-

T a b l e 7. Sums of values of the output variables for samples fulfilling the criterion *S* and the measure (*N*) of the separation effectiveness of particular type of mixture

Sample no.	Type of mixture					
	PLA/PVC	PLA/PET	PCL/PVC	PCL/PET	P(3,4HB)/PVC	P(3,4HB)/PET
3	–	–	313.6	–	–	–
4	321.6	323.0	–	324.2	–	384.9
8	–	–	–	–	329.9	–
11	291.1	–	–	–	–	399.7
12	–	–	–	289.7	–	–
16	–	239.0	238.8	–	247.0	–
17	292.0	278.4	310.1	249.9	267.6	250.8
18	210.0	152.7	189.3	184.5	154.8	395.2
19	–	–	–	301.0	–	–
22	–	314.2	–	–	276.6	384.8
24	–	–	286.0	–	–	–
28	313.3	–	–	–	–	–
N	0.71	0.65	0.67	0.67	0.64	0.91

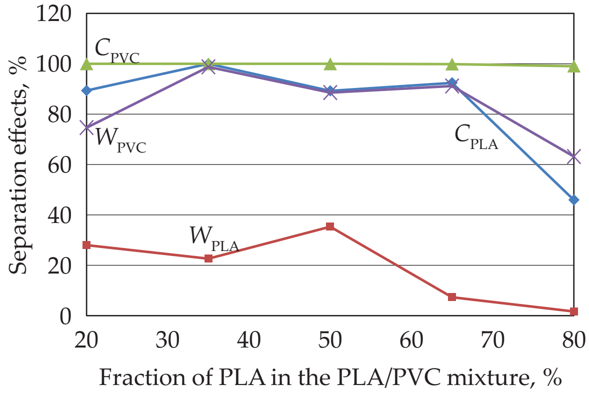

Fig. 1. Effects of separation of the PLA/PVC mixture as functions of contribution of PLA

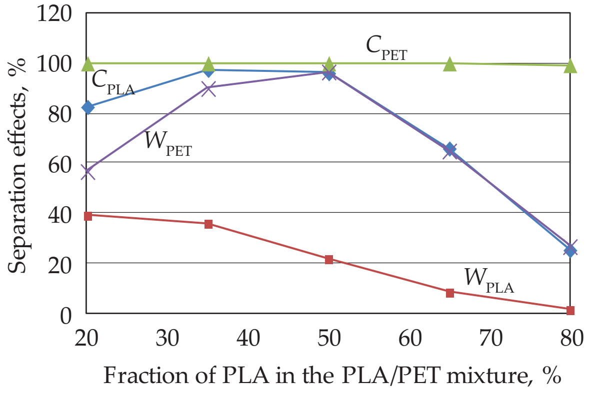

Fig. 2. Effects of separation of the PLA/PET mixture as functions of contribution of PLA

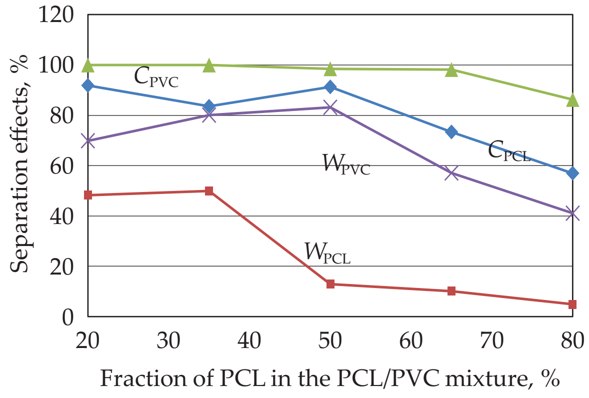

Fig. 3. Effects of separation of the PCL/PVC mixture as functions of contribution of PCL

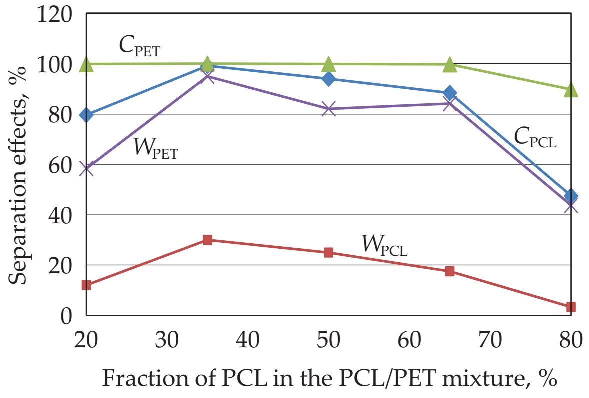

Fig. 4. Effects of separation of the PCL/PET mixture as functions of contribution of PCL

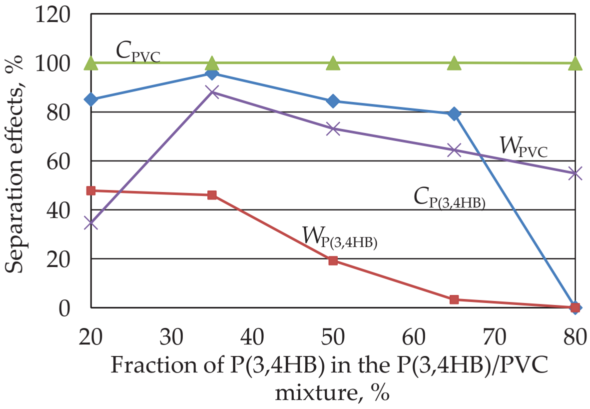

Fig. 5. Effects of separation of the P(3,4HB)/PVC mixture as functions of contribution of P(3,4HB)

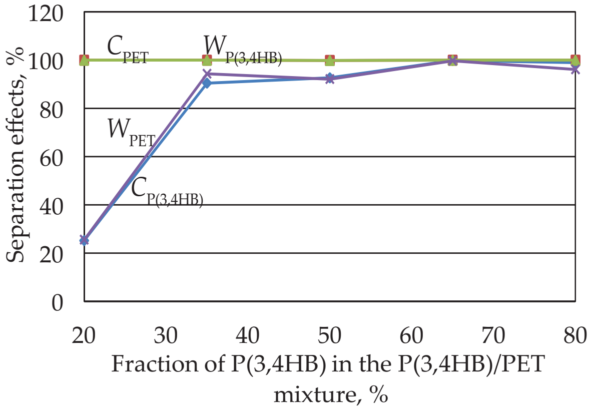

Fig. 6. Effects of separation of the P(3,4HB)/PET mixture as functions of contribution of P(3,4HB) (the lines for samples $W_{P(3,4HB)}$ and C_{PET} are overlapping each other)

sented in Table 7 the effectiveness of the separation process is highest for the P(3,4HB)/PET mixture and lowest for the P(3,4HB)/PVC mixture.

The results obtained in this work point out that the separator parameters should be fitted to the separation of a given mixture, depending on the mass fractions of the mixture components. Selection of these parameters is determined by a preferred purpose of the separation, expressed as the criterion *S* for the values of the output variables. If the separation effects are not satisfactory, then a multistep separation may be applied. This requires the use of a multistep separator or a repetition of the separation using a single-step separator.

CONCLUSIONS

The presented results indicate that the electrostatic separation may be successfully applied to sorting of binary mixtures of a biodegradable polymer [PLA, PCL, or P(3,4HB)] and a commonly used polymer (PVC or PET). Two groups of variables influencing the separation effects were examined. One of them was constituted by properties of the studied mixtures, especially types and mass fractions of the polymers – components of the mixture. The other group comprised three quantities characterizing conditions under which the separation process is being carried out and considered as the separator parameters, namely the tribocharging time, potential difference between the separator electrodes, and rotational speed of the earthed cylindrical electrode.

It is demonstrated that the mass fractions of the mixture components essentially influence effects of the electrostatic separation. The most beneficial results of this process were obtained when the fractions of the biodegradable polymers were generally 35–65 wt % and in the case of the P(3,4HB)/PET mixture, 35–80 wt %. For this mixture the effectiveness of the electrostatic separation process is the highest as compared with all other mixtures.

Selection of conditions for carrying out the electrostatic separation, especially the separator parameters, depends on both the mass fractions of the mixture components and the criterion *S*. The procedure for fitting the separator parameters to the separation of a mixture of fixed mass fractions of individual components may easily be adapted to a definite separation process.

REFERENCES

[1] Goodship V.: "Introduction to Plastics Recycling", Smithers Rapra Technology Ltd., Shawbury 2007.
[2] Chowdhury M.: *Waste Management* **2009**, *29*, 2240. http://dx.doi.org/10.1016/j.wasman.2009.04.005
[3] Al-Salem S.M., Lettieri P., Baeyens J.: *Waste Management* **2009**, *29*, 2625. http://dx.doi.org/10.1016/j.wasman.2009.06.004
[4] Hamad K., Kaseem M., Deri F.: *Polymer Degradation and Stability* **2013**, *98*, 2801. http://dx.doi.org/10.1016/j.polymdegradstab.2013.09.025
[5] Wu G., Li J., Xu Z.: *Waste Management* **2013**, *33*, 585. http://dx.doi.org/10.1016/j.wasman.2012.10.014
[6] Reinsch E., Frey A., Albrecht V. *et al.*: *Chemie Ingenieur Technik* **2014**, *86*, 784. http://dx.doi.org/10.1002/cite.201400010
[7] Li J., Wu G., Xu Z.: *Waste Management* **2015**, *35*, 36. http://dx.doi.org/10.1016/j.wasman.2014.10.001
[8] Higashiyama Y., Ujiie Y., Asano K.: *Journal of Electrostatics* **1997**, *42*, 63. http://dx.doi.org/10.1016/S0304-3886(97)00131-9
[9] Dodbiba G., Shibayama A., Miyazaki T., Fujita T.: *Magnetic and Electrical Separation* **2002**, *11*, 63. http://dx.doi.org/10.1080/07313630290002626
[10] Dodbiba G., Fujita T.: *Physical Separation in Science and Engineering* **2004**, *13*, 165.
[11] Park C.H., Park J.K., Jeon H.S., Chun B.C.: *Journal of Electrostatics* **2008**, *66*, 578. http://dx.doi.org/10.1016/j.elstat.2008.07.001

[12] Lee J-K., Shin J-H.: *Korean Journal of Chemical Engineering* **2003**, *20*, 572.
http://dx.doi.org/10.1007/BF02705568

[13] Iuga A., Calin L., Neamtu V. *et al.*: *Journal of Electrostatics* **2005**, *63*, 937.
http://dx.doi.org/10.1016/j.elstat.2005.03.064

[14] Brück R.: *Kunststoffe* **1981**, *71*, 234.

[15] Diaz A.F., Felix-Navarro R.M.: *Journal of Electrostatics* **2004**, *62*, 277.
http://dx.doi.org/10.1016/j.elstat.2004.05.005

[16] Gooding D.M., Kaufman G.K.: "Encyclopedia of Inorganic and Bioinorganic Chemistry", John Wiley & Sons Ltd., New York 2014, pp. 1–9.
http://dx.doi.org/10.1002/9781119951438

[17] Auras R.A., Lim L-T., Selke S.E.M., Tsuji H. (Eds.): "Poly(lactic acid), Synthesis, Structures, Properties, Processing, and Applications", John Wiley & Sons Inc., New York 2010.
http://dx.doi.org/10.1002/9780470649848

[18] Lim L-T., Auras R., Rubino M.: *Progress in Polymer Science* **2008**, *33*, 820.
http://dx.doi.org/10.1016/j.progpolymsci.2008.05.004

[19] Stepczyńska M.: *Polimery* **2015**, *60*, 462.
http://dx.doi.org/10.14314/polimery.2015.462

[20] Moraczewski K., Malinowski R., Rytlewski P., Żenkiewicz M.: *Polimery* **2015**, *60*, 492.
http://dx.doi.org/10.14314/polimery.2015.492

[21] Woodruff M.A., Hutmacher D.W.: *Progress in Polymer Science* **2010**, *35*, 1217.
http://dx.doi.org/10.1016/j.progpolymsci.2010.04.002

[22] Nair L.S., Laurencin C.T.: *Progress in Polymer Science* **2007**, *32*, 762.
http://dx.doi.org/10.1016/j.progpolymsci.2007.05.017

[23] Laycock B., Halley P., Pratt S. *et al.*: *Progress in Polymer Science* **2013**, *38*, 536.
http://dx.doi.org/10.1016/j.progpolymsci.2012.06.003

[24] Wang L., Wang X., Zhu W., Chen Z. *et al.*: *Journal of Applied Polymer Science* **2010**, *116*, 1116.
http://dx.doi.org/10.1002/app.31588

[25] Reddy M.M., Vivekanandhan S., Misra M. *et al.*: *Progress in Polymer Science* **2013**, *38*, 1653.
http://dx.doi.org/10.1016/j.progpolymsci.2013.05.006

[26] Brzeska J., Dacko P., Janeczek H. *et al.*: *Polimery* **2014**, *59*, 365.
http://dx.doi.org/10.14314/polimery.2014.365

[27] Żenkiewicz M., Richert J., Rytlewski P. *et al.*: *Polymer Testing* **2009**, *28*, 412.
http://dx.doi.org/10.1016/j.polymertesting.2009.01.012

[28] Moraczewski K.: *Polymer Testing* **2014**, *33*, 116.
http://dx.doi.org/10.1016/j.polymertesting.2013.11.010

[29] Moraczewski K.: *Polymers for Advanced Technologies* **2016**, *27*, 733. http://dx.doi.org/10.1002/pat.3706

[30] Żenkiewicz M., Żuk T., Błaszkowski M., Szumski Z.: *Przemysł Chemiczny* **2013**, *92*, 279.

[31] Żenkiewicz M., Żuk T., Markiewicz E.: *Polymer Testing* **2015**, *42*, 192.
http://dx.doi.org/10.1016/j.polymertesting.2015.01.009

[32] Polański Z.: „Metodyka badań doświadczalnych", WPK, Kraków 1981.

[33] Korzyński M.: „Metodyka eksperymentu", WNT, Warszawa 2006.

[34] Żenkiewicz M., Żuk T.: *Przemysł Chem*iczny **2014**, *93*, 54.

[35] Żenkiewicz M., Żuk T.: *Polimery* **2014**, *59*, 314.
http://dx.doi.org/10.14314/polimery.2014.314

[36] Żenkiewicz M., Żuk T., Błaszkowski M.: *Polimery* **2014**, *59*, 495.
http://dx.doi.org/10.14314/polimery.2014.495

[37] Żuk T., Pietraszak J., Żenkiewicz M.: *Polimery* **2016**, *61*, 519.
http://dx.doi.org/10.14314/polimery.2016.519

Received 17 II 2016.