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INVESTIGATION AND EVALUATION OF JIGGING SEPARATION FEATURES

BADANIA I OCENA ARGUMENTU ROZDZIAŁU W OSADZARCE

The process of enrichment in a jig has usually been described and analysed using particle density as a separation feature. However, a degree of particle loosening in the jig bed is affected by, inter alia, the terminal particle free settling velocity which in turn is affected by the size, density and shape of a particle. Therefore, the terminal particle settling velocity clearly characterises the feed transferred to a jig for the enrichment process. Taking the comprehensive particle geometric (particle size and shape) and physical properties (particle density) into account comes down to the calculation of the terminal particle settling velocity. The terminal particle settling velocity is therefore a complex separation feature which comprises three basic particle features (particle density, size and shape).

This paper compares the effects of enrichment of coal fines in a jig, for two cases: when the commonly applied particle density is separation feature and for the particle settling velocity. Particle settling velocities were calculated in the selected three particle size fractions: –3.15+2.00, –10.00+8.00 and –20.00+16.00 mm based on the industrial testing of a jig for coal fines and detailed laboratory tests consisting in determining particle density, projective diameter and volume and dynamic particle shape coefficient. The calculated and drawn partition curves for two variants, i.e. when particle density and particle settling velocity were taken into account as the separation argument in selected particle size fractions, allowed to calculate and compare separation precision indicator. With the use of a statistical test, the assumption on the independence of random variables of the distribution of components included in the distribution of the particle settling velocity as a separation feature during enrichment in a jig was verified.

Keywords: jig separation feature, particle size, particle density, shape coefficient, particle settling velocity, separation precision

Zazwyczaj proces wzbogacania w osadzarce opisywano i analizowano przy użyciu gęstości ziaren jako cechy rozdziału. Jednakże na stopień rozluzowania ziaren w łożu osadzarki ma wpływ między innymi graniczna prędkość opadania swobodnego ziarna, na którą ma wpływ wielkość, gęstość i kształt ziarna. Zatem graniczna prędkość opadania ziaren w sposób jednoznaczny charakteryzuje nadawę

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kierowaną do procesu wzbogacania w osadzarce. Uwzględnienie kompleksowych właściwości geometrycznych ziaren (wielkość i kształt ziaren) oraz fizycznych (gęstość ziaren) sprowadza się do wyliczenia granicznej prędkości opadania ziaren. Zatem graniczna prędkość opadania ziaren jest to złożona cecha rozdziału zawierająca w sobie trzy podstawowe cechy ziarna (gęstość, wielkość i kształt ziarna). W tej pracy porównano efekty wzbogacania miałów węglowych w osadzarce dla dwóch przypadków: kiedy cechą rozdziału jest powszechnie stosowana gęstość ziaren oraz dla prędkości opadania ziaren. Na podstawie opróbowania przemysłowego osadzarki miałowej i szczegółowych badań laboratoryjnych, polegających na określeniu gęstości ziaren, średnicy projekcyjnej i objętościowego oraz dynamicznego współczynnika kształtu ziaren wyliczono prędkości opadania ziaren w wybranych trzech klasach ziarnowych: 2.0-3.15, 8.0-10.0 i 16.0-20.0 mm. Wyliczone i wykreślone krzywe rozdziału dla dwóch wariantów tzn. kiedy brano pod uwagę gęstość ziaren i prędkość opadania ziaren jako argument rozdziału w wybranych klasach ziarnowych, pozwoliły na wyliczenie i porównanie wskaźników dokładności rozdziału. Przy pomocy testu statystycznego dokonano weryfikacji założenia o niezależności zmiennych losowych rozkładu składowych wchodzących w skład rozkładu prędkości opadania ziaren jako cechy rozdziału przy wzbogacaniu w osadzarce.

Słowa kluczowe: wielkość ziaren, współczynnik kształtu, cecha rozdziału w osadzarce, gęstość ziaren

1. Introduction

The enrichment of coal fines in Poland is performed mainly in the water medium in jigs for coal fines (Osoba, 2017). The operational precision of these separating devices affects qualitative parameters of produced commercial assortments. Accumulation of heavy and light particles in individual layers in the working bed of a jig is the result of the pulsating movement of mineral particles suspended in a water stream. This occurs as a result of differences in physical and geometric properties of separated particles, i.e. density of individual particles of the separated feed, their size and geometric shapes. The sufficient loosening of particles in the jig's working space is the essential condition for mineral particles set in the pulsating movement to occupy the appropriate positions. The degree of particles' stratification within the jig's working space and the effect of various parameters on particles' stratification are described by various models (Leyman, 1992; Mishra & Mehrotra, 1998; Mukherjee & Mishra, 2007; Xia et al., 2007; Viduka et al., 2011; Viduka et al., 2013), but so far there has been no theory which would explicitly describe the particle separation mechanism. The degree of particle loosening in the jig's bed is affected, *inter alia*, by the particle settling velocity. The distance to be covered by a particle during one pulsation cycle depends on the particle settling velocity. Hence, after some time of a pulsating movement, particles will undergo segregation along the vertical axis, according to the settling velocity. It can be thus said that the particle settling velocity constitutes a feature which characterises a set of the feed particles that are heterogeneous in terms of physical and geometric properties during the separation process in a jig.

Therefore, the settling velocity constitutes the separation argument in processes of hydraulic classification and separation in a jig. The knowledge of the settling velocity distribution enhances the analysis of separation in these processes. Since the particle settling velocity is the function of particle physical and geometric features, it will be affected by particle density, size and shape. Based on the adopted assumption that distributions of particle density, size and shape constitute random variables with specified distributions, algorithms for the calculation of the particle settling velocity distribution in a monodispersion and polydispersion sample of spherical and irregular particles were developed (Brożek & Surowiak, 2007; Surowiak, 2014; Surowiak & Brożek, 2014a; 2014b; 2016). Based on the empirical research on the randomly selected sample of particles from the selected particle size fractions, density, size and shape were determined in this paper for every particle. The obtained data allowed to calculate particle settling velocities, and using the statistical test, to verify the adopted assumption of the independence of random variables affecting separation precision in a jig.

Partition curves are usually used in the practice of enrichment and evaluation of separation results when particle density is the separation argument. Density is the separation argument in the case of enrichment of a sample of monodispersion spherical particles. Then, geometric properties have fixed values identical for all particles, and the settling velocity distribution depends only on the particle density distribution. Although the particle density distribution in the sample is independent of the geometric properties' distribution, the evaluation of the device's separation precision based on density in which stratification of particles occurs according to the settling velocity suffers from a certain error due to the existence of the innate possible error, independent of the process course conditions and dependent on the geometric properties' distribution (Surowiak & Brożek, 2016).

The article presents and compares the evaluation of the effects of enrichment of coal fines in a jig, in the case when particle density and settling velocity are the separation feature. A dependence derived on the basis of heuristic considerations, defined by the following formula was used to calculate the particle settling velocity (Brożek & Surowiak, 2010):

$$v = 5.33\sqrt{x}\sqrt{d_p}\sqrt{\left(\frac{k_1}{k_2}\right)} \tag{1}$$

Where: $x = \dfrac{\rho - \rho_0}{\rho_0}$ – reduced particle density, ρ – particle density, ρ_o – liquid density, d_p – particle projective diameter, k_1 – volume shape coefficient, k_2 – dynamic shape coefficient.

Formula (1), describing the irregular particle settling velocity, which combines particle projective diameter, reduced density and particle shape coefficients, was used to calculate the terminal particle settling velocity in a jig. The method presented in the article concerning the evaluation of enrichment effects when the velocity of particles settling in a separating device – a jig, is the separation feature, is a different attempt to approach the generally known issue; nevertheless significant from the perspective of the technological enrichment of coal fines.

2. Materials and methods

The aim of the experimental research was to determine the settling velocity of coal particles in the feed and separation products in a jig and to compare separation precision in the case when particle density and particle settling velocity were used as the separation argument. The first stage of the research involved testing the Allmineral two-product industrial jig with a working surface area of 17 m^2 operating at the mechanical processing plant in one of bituminous coal mines. The researched material – coal fines – was characterised by mean ash contents equal to about 51.3%. The system efficiency, i.e. the capacity of the feed flow to the jig was equal to 500 Mg/h. With the established parameters and after the process stabilisation, samples from the feed, concentrate and tailings were collected within 3 minutes, each at the same time. Then, each separation product (concentrate and tailings) was subjected to the to flow and sink analysis carried out in zinc chloride solutions with the following densities: 1.30; 1.40; 1.50; 1.60; 1.70; 1.80; 2.00 Mg/m^3 respectively. Each densimetric fraction was sieved through sieves with the following sizes: 2.00; 3.15; 5.00; 6.30; 8.00; 10.00; 12.50; 16.00; 20.00 mm. Obtained results of the experiments allowed to determine the separation precision based on the partition curve and partition numbers taking particle density as the separation argument into account.

Partition numbers were calculated for tailings of coal fines using the dependence:

$$T_\rho = \frac{n_T}{n_F} \tag{2}$$

where: T_ρ – partition number for particles with density ρ, n_T – number of particles with density ρ directed to tailings, n_F – number of particles of this density in the feed.

Formula (2) presents the probability that a particle with density ρ will get to tailings.

The second stage of the experiment focused on the determination of the settling velocity of particles separated in the jig and statistical evaluation of mutual dependencies between variables affecting the settling velocity. To this end, the following elements were measured: particle projective diameter, specific density and shape coefficients. Measurement results are presented in Tables 1-3 in Appendix 1. Similarly, partition numbers were calculated for the particle settling velocity as a separation feature. For both cases, separation precision indicators, i.e. probable error E_p and imperfection I were calculated from partition curves.

2.1. Measurement of the projective diameter and particle shape coefficients

Volume shape coefficient k_1 was determined based on the volumetric method consisting in measuring density of individual particles using a pycnometer and calculating their volume. Shape coefficient k_1 was calculated using the following formula:

$$V = k_1 \frac{\pi d_p^3}{6} \tag{3}$$

where: $d_p = \sqrt{\frac{4S}{\pi}}$, and S – particle projective surface area

In order to calculate the particle projective surface area and the dynamic particle shape coefficient, digital photographic images were taken in the most stable position. Photographs 1 and 2 present for example the manner of determining geometric measures of particles of size fractions –3.15+2.00 and –20.00+16.00 mm. Then, particle projective areas and perimeters of individual particles were calculated using the SigmaScanPro computer software for image analysis. Sphericity coefficients φ were determined using the following formula (4):

$$\varphi \cong k_c = \left(\frac{C}{C_z}\right)_s \tag{4}$$

where: C_z – perimeter of the particle projective surface, C – perimeter of a circle with the surface area equal to the particle projective surface area.

Dynamic shape coefficient k_2 was calculated from the following formula provided by Ganser (1993):

$$k_2 = 10^{1,8148(-\log\varphi)^{0,5743}} \tag{5}$$

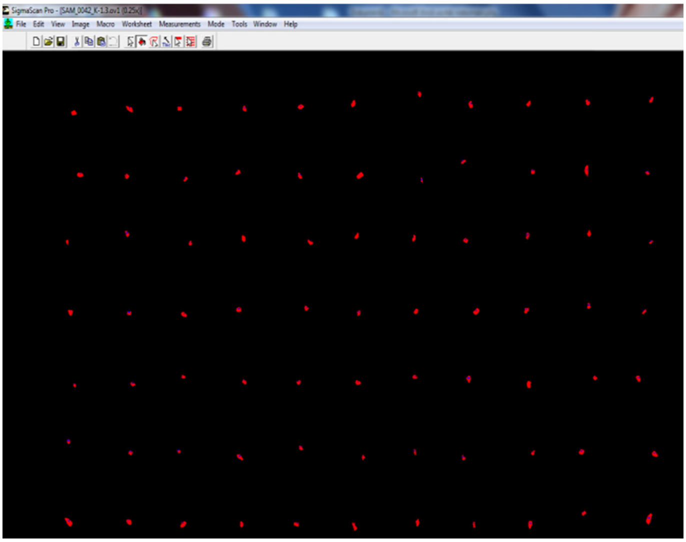

Photo. 1. Size fraction –3.15+2.00 mm

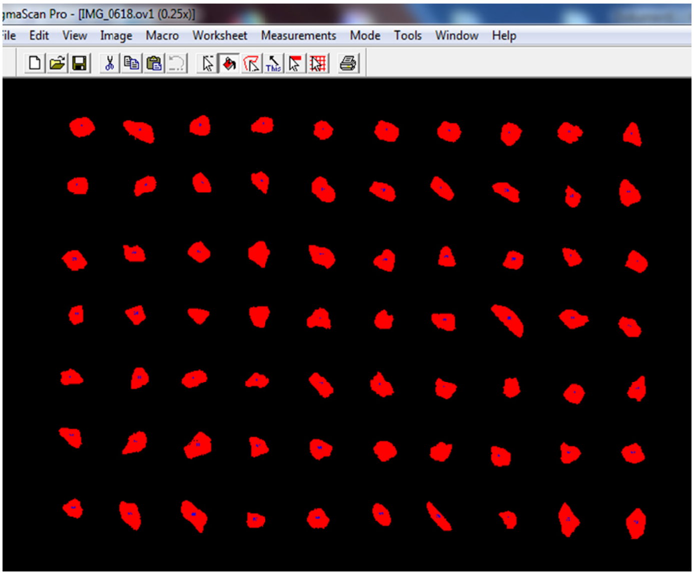

Photo. 2. Size fraction –20.00+16.00 mm

3. Results and discussion

For the purposes of this paper, coordinates were calculated and partition curves were drawn for the case when particle density and particle settling velocity are the separation argument for the selected three narrow particle size fractions, i.e. two extreme and one middle size fraction from the feed granulation for the jig: –20.00+16.00, –10.00+8.00 and –3.15+2.00 mm. Table 1 presents mass yields of the class fraction obtained for selected size fractions from the industrial testing of the obtained separation products in the jig. Based on this data, coordinates of partition curves for tailings in narrow particle size fractions were calculated.

3.1. The analysis of separation precision with particle density as the separation feature

Partition curves are usually used to evaluate the effects of enrichment of coal fines in a jig when particle density is the separation argument. In this case, coordinates of partition curves, the so-called partition numbers $T(\rho)$ for tailings were calculated with the use of formula (2).

According to many authors (Gottfried, 1978; Paul et al., 1998; Surowiak, 2018), partition curves for jigs with density as the separation argument are asymmetric curves and are well approximated by the Weibull distribution. Hence, the Weibull distribution, the general form of which is provided by equation (6) was matched to the empirical partition curve:

$$T(\rho) = 100\left\{1 - \exp\left[-\left(\frac{\rho}{\rho_o}\right)^n\right]\right\} \tag{6}$$

where: ρ_o and n – denote separation parameters.

Graphs of cumulative distribution functions of partition curves along with separation parameters are shown in Figures 1-3. The continuous curve in these figures represents the model dependence. The MSE (the mean square error) indicator was used to evaluate the distribution match (Tumidajski & Saramak, 2009). Using the approximated partition curves, separation precision indicators, i.e. separation density ρ_r, probable error E_p and imperfection I were calculated; their values are shown in Table 2.

TABLE 1

Mass yields of class fractions of separation products

Size fraction [mm]	Density fraction, Mg/m^3															
	–1.3		1.3-1.4		1.4-1.5		1.5-1.6		1.6-1.7		1.7-1.8		1.8-2.0		+2.0	
	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T
–3.15+2.00	1471.7	120.0	508.9	81.6	217.2	96.7	14.6	81.5	8.3	269.8	6.3	434.6	8.3	690.4	8.3	1962.3
–10.00+8.00	1767.0	36.5	787.5	46.7	346.9	39.7	28.8	53.9	12.8	179.9	12.2	263.2	15.8	1094.4	7.4	3211.1
–20.00+16.00	1614.7	13.9	597.6	34.5	524.7	80.7	28.9	107.8	28.9	213.4	12.7	393.5	3.4	1380.6	3.4	5722.2

C – concentrate (g), *T* – tailings (g)

Separation precision indicators presented in Table 2 indicate the best separation effectiveness for size fraction –10.00+8.00 mm. Imperfection is the lowest of all the analysed particle size fractions and equals to 0.185 with simultaneously the greatest separation density equal to 1.63 Mg/m^3.

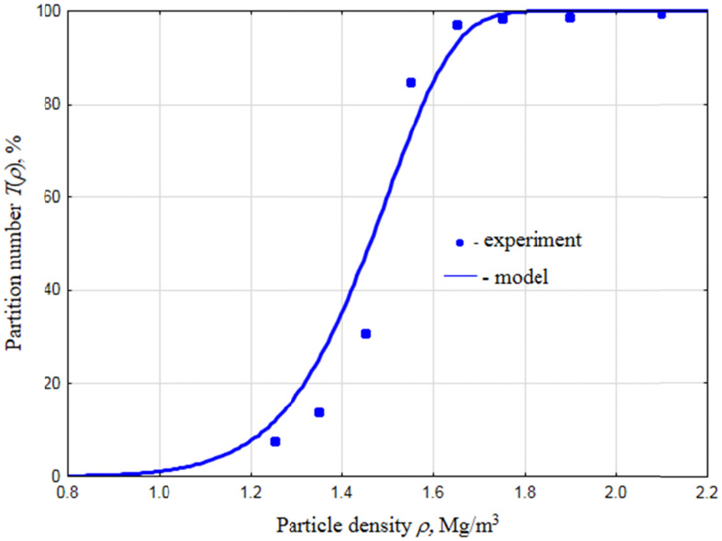

Fig. 1. The partition curve of size fraction –3.15+2.00 mm, ρ_o = 1.51 Mg/m^3, n = 10.99, MSE = 8.4%

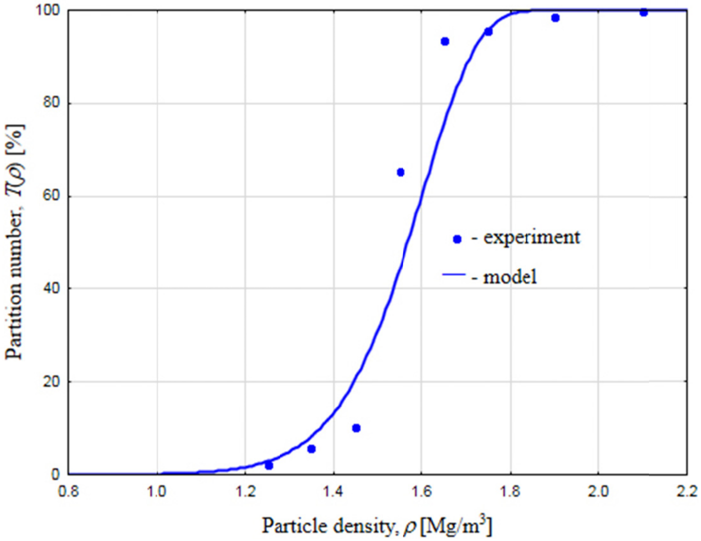

Fig. 2. The partition curve of size fraction –10.00+8.00 mm, ρ_o = 1.61 Mg/m^3, n = 13.94, MSE = 10.4 %

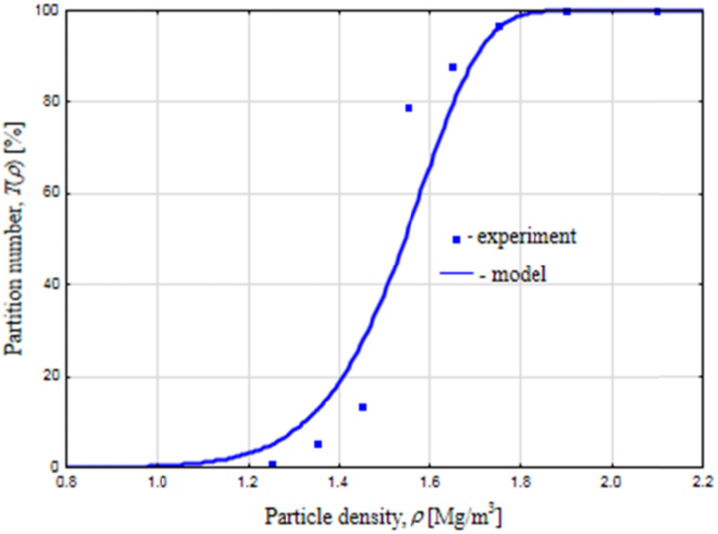

Fig. 3. The partition curve of size fraction –20.00+16.00 mm, ρ_o = 1.59 Mg/m^3, n = 12.35, MSE = 13.4 %

3.2. The analysis of separation precision with the particle settling velocity as the separation argument

The determined values of component quantities affect the particle settling velocity, i.e. size of particles is expressed by projective diameter d_p, their shape as the quotient of volume shape coefficient k_1 and dynamic shape coefficient k_2 and reduced particle density x, allowed to calculate the particle settling velocity in individual particle size fractions using formula (1). In the case of calculation of the reduced density, the presence of fine particles of the solid phase in the jig's whitewater was taken into account. Hence, liquid density equals to 1.093 Mg/m^3.

The partition curve, when the terminal particle settling velocity is the separation feature, has a form of a cumulative normal distribution function. This allows to assume the hypothesis that the vertical component distribution of the particle velocity in a jig around the most probable value is the Maxwell distribution of the velocity component which is the normal distribution (Smirnova, 1980). Hence, the determined coordinates of the partition curve were approximated by the normal distribution. Figures 4-6 present cumulative distribution functions of partition curves with the particle settling velocity as the separation argument. The calculated MSE values at the level below 10% indicate that there is very high matching compliance with empirical data.

The analysis of separation precision indicators in the case when the particle settling velocity is assumed as the separation feature indicates that the best separation effects were achieved in size fraction –10.00+8.00 mm. Imperfection in this case is equal to 0.108. The values of E_p are the lowest in all analysed particle size fractions with the highest separation velocity of the examined particle size fractions. In the remaining particle size fractions, imperfection is equal to 0.16 and 0.18 respectively and the highest probable error E_p = 0.25 m/s is observed in the finest size fraction –3.15+2.00 mm, similarly as it occurs in the case of the analysis of the process with particle density as the separation argument.

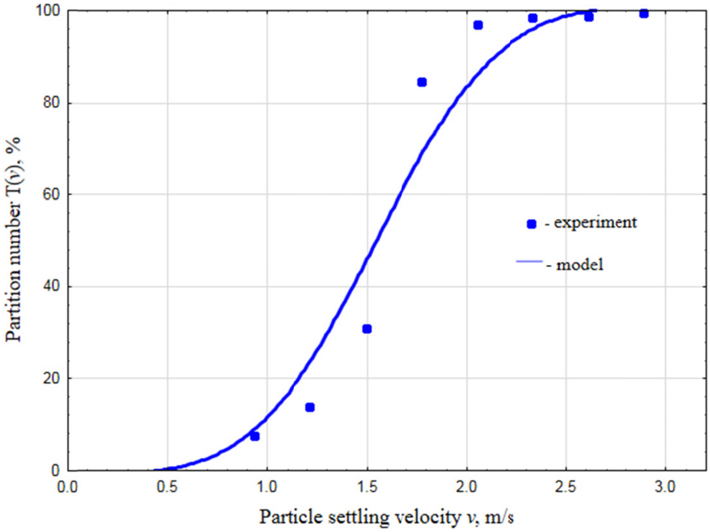

Fig. 4. The partition curve of size fraction –3.15+2.00 mm, MSE = 8.0%

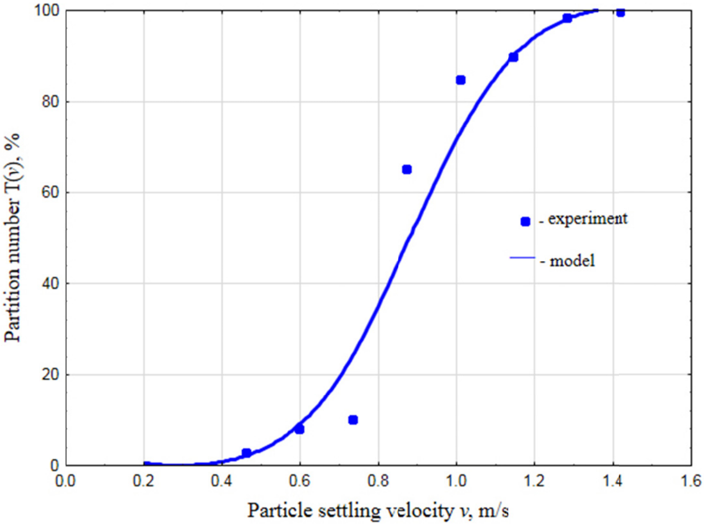

Fig. 5. The partition curve of size fraction –10.00+8.00 mm, MSE = 9.2%

While evaluating separation results in the case when particle density was the separation feature, a higher imperfection value than in the case when the particle settling velocity was the separation feature was found. This is caused by the phenomenon of particles' dispersion to inappropriate products. The difference is the contribution originated in the innate dispersion, the value of which depends on the distribution of geometric features (Surowiak & Brożek, 2016).

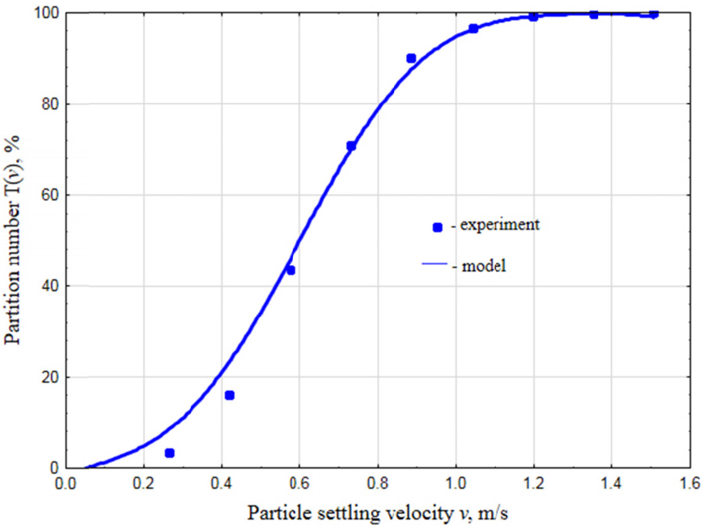

Fig. 6. The partition curve of size fraction +16.00-20.00 mm, MSE = 1.54%

TABLE 2

Separation precision indicators depending on the analysed separation feature

Indicator	**Particle size, mm**		
	–3.15+2.00	**–10.00+8.00**	**–20.00+16.00**
	Separation feature: particle density		
Separation density ρ_r, Mg/m^3	1.45	1.63	1.56
Probable error E_p, Mg/m^3	0.104	0.088	0.098
Imperfection I	0.218	0.185	0.307
	Separation feature: particle settling velocity		
Separation velocity v_r, m/s	1.55	0.73	0.62
Probable error E_p, m/s	0.250	0.095	0.115
Imperfection I	0.161	0.108	0.183

3.3. The analysis of dependencies of random variables affecting the particle settling velocity in a jig

As mentioned above, the particle settling velocity is the separation argument in the enrichment process in a jig. In accordance with formula (1), the terminal particle settling velocity is the function of this particle's density, size and shape coefficients. The feed directed to the separation process is characterised by the distribution of particle physical and geometric properties, and in this connection, also by particle settling velocities. Assuming that reduced density x, projective diameter d_p and shape coefficients k_1 and k_2 are independent random variables, the particle settling velocity also constitutes a random variable which is the function of the aforementioned random variables. The nature of the settling velocity distribution depends on distributions of random variables in formula (1). Having values of individual random variables and using probability calculus theorems that refer to functions of random variables allows to calculate the distribution of the particle settling velocity by converting it into the form being the product of two random variables. The methodology of converting the settling velocity distribution into the form being the product of two random variables was described in papers by Brożek and Surowiak (2004, 2005) and Surowiak and Brożek (2014 a,b).

With empirical values of particular components of formula (1), determined on a random sample of particles in selected particle size fractions, the assumption of dependence of random variables was verified using the chi-square statistical test for independence of random variables.

Particle density ρ_s was denoted as variable "1", particle projective diameter d_p as variable "2" and quotient of shape coefficients k_1/k_2 as variable "3".

Calculations of dependency combinations were performed for variables 1 and 2, 1 and 3, and 2 and 3 respectively. For this purpose, matrices of results were formulated for the individual pairs of variables. Results of the statistical analysis are presented in Table 3. The dependence of variables was verified based on dependence (7) and compared with the table value for the calculated number of degrees of freedom at the statistical significance level of 0.05.

$$\chi^2 = \sum_{i=1}^{s} \sum_{j=1}^{r} \frac{(n_{ij} - np_{ij})^2}{np_{ij}} \tag{7}$$

where: n – amount of observation, p_{ij} – probability of observation occurrence in cell ij, n_{ij} – amount of observation in cell ij

TABLE 3

Results of the chi-square test in particle size fractions

Particle size [mm]	**Variable 1 and 2 (ρ_s and dp)**	**Variable 1 and 3 (ρ_s and k_1/k_2)**	**Variable 2 and 3 (dp, and k_1/k_2)**
–3.15+2.0	dependent	dependent	dependent
–10.00+8.00	independent	dependent	dependent
–20.00+16.00	independent	dependent	dependent

The statistical analysis of dependencies between random variables using the chi-square test has shown that variables such as particle density and projective diameter in average and coarse particle size fractions are independent variables. However, these variables in the finest size fraction –3.15+2.00 mm are dependent. The analysed variables, i.e. particle density and quotient of shape coefficients as well as projective diameter and quotient of shape coefficients are mutually dependent in all analysed particle size fractions. The unambiguous identification of dependencies or independencies of these variables will be possible after such statistical analyses are performed in the remaining particle size fractions and in the feed directed to be enriched in a jig. Then, it will be possible to clearly verify the adopted assumption on the independence of the distributions of random variables being component functions of the separation argument – the particle settling velocity in a jig, i.e. distributions of physical and geometric properties of particles.

6. Conclusions

The description of the enrichment process in a jig and calculation of the partition curve, as well as separation precision indicators and the description of this precision based on the particle settling velocity as the separation feature is the approach different from the one used to date. The application of this evaluation method allows to conclude that the precision of separation in a jig is actually higher than the analysis of separation evaluated on the basis of density relations indicates. This results from the fact that the settling velocity as the separation feature includes, apart from density, additional features differentiating particles between each other. This allows to qualify particles more precisely to the proper sub-layer during the separation process. In connection with this, values of separation precision indicators such as imperfection assume lower values in the case when the process precision is analysed through the particle settling velocity as the separation argument. Even within the analysed narrow particle size fractions in which the negligible effect of particle size on the settling velocity can be assumed, particle shape coefficients, apart from particle density, affect the settling velocity. In the face of that, taking the comprehensive geometric (size and shape) and physical properties (density) of particles into account comes down to the calculation of the terminal particle settling velocity. Therefore, the terminal particle settling velocity is the complex separation feature which comprises three basic particle features (density, size and shape of the particle).

The assumption of independence of distributions of random variables of particle physical (density) and geometric properties (size and shape) was successfully verified for the distribution of density and projective diameter of particles in two selected particle size fractions. This assumption was not confirmed in the case of the finest particles. Results of the conducted analyses induce to conduct measurements of density, projective diameter and quotient of particle shape coefficients in the remaining particle size fractions enriched in a jig. The analysis of the statistical verification presented in this paper, carried out within the full particle size range of the feed directed to a jig will allow to fully describe the problem and simultaneously state whether random variables affecting the particle settling velocity in a jig are dependent or not. This will be the subject of the research in the successive stages of implementation of this issue.

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