Economical Efficiency Assessment of an Application of On-line Feed Particle Size Analysis to the Coal Cleaning Systems in Jigs

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Summary

In the currently used coal cleaning plants, coal concentrate quality is determined by on-line measurement of the concentrate ash content. The cleaning process in the jig is quite sensitive to the feed particle size distribution. For this reason, the on-line video analysis of feed particle size distribution enables faster (up to a few minutes) reaction of the control system to changes in grain size composition, resulting in the concentrate production with more time-stable qualitative parameters (ash content). As a result, it can lead to an increase in the production value. In this paper there has been made an attempt to assess the extent to which the on-line analysis of feed particle size distribution of the feed- to cleaning systems with one or two and three jigs can improve the cleaning efficiency.

Keywords: partile size analysis, jig, coal beneficiation, economical efficiency

Introduction

The quantity and quality of cleaning product depend on the washability of raw coal, coal preparation processes in the technological system of coal cleaning, separation parameters of these operations and cleaning imperfection. Cleaning inaccuracy results from the fact that the enrichment process does not proceed perfectly, therefore the shape of the separation curves is not perfect [2, 5, 10-12], By means of these curves gravity separation processes are modeled. The shape of these curves depends on the size of the particles - the smaller are the grains, the worse is the shape of these curves, the more deviates from their ideal shape and cleaning inaccuracy. In this paper there are considered jig cleaning systems, therefore in Fig. 1 shows a set of several separation curves of the two-product jig, These curves characterize the jig operation for different size classes of feed particles. This figure only shows the distribution curves that have been used in the simulation forecasts as the feed grain size composition is limited to the 3 size fractions, described in Table 1.

In p. 2 there are described the feed washability characteristics and different layouts of considered jig cleaning technological systems. In p. 3.1 there have been presented the determined optimum separation densities. Then, to examine the effect of changes of particle size distribution it has been assumed that the feed consists of two streams N1 and N2 (Tab. 3), mixed in such proportions that their total share is always equal to 100%. The increase in the share of N1 feed stream from 0% to 100% corresponds to the reduction in the N2 feed stream from 100% to 0%. If shares of both the feed streams N1 and N2 are equal to 50%, then the contributions of all three grain size fractions are approximately equal - such as in the Tab. 1. This is the case regarded as the initial situation (p. 3.1) and further (p. 4) is regarded as cleaning without grain size composition disturbances. Because the washability curve is identical for all particle size fractions (Tab. 2), so the change in N1 and N2 feed streams shares only cause changes in grain size composition but without changes in washability characteristics. The analyses presented further (p.3.2) illustrate only the impact of grain size composition changes on the cleaning effects. In p. 3.3 there have been shown recalculated optimum separation densities but for different shares of N1 and N2 feed streams. Accordingly fast reaction of the jig control system to changes in grain size composition results in a stabilization of production quality (ash content in the concentrate).

The authors have assumed that all N1 and N2 feed stream share different from the 50% are regarded as disturbances of feed grain size composition. In p. 4 there are shown the results of analyzes of production value in conditions of grain size composition disturbances. We have compared the work of technological systems controlled only by an on-line measurement of the concentrate ash content (a basic solution) with an innovative control with additional on-line visual analysis of the feed grain size composition.

Considered jig coal cleaning technological systems

In the analyzes presented in this paper for calculations there have been assumed hardly washable characteristics of raw coal. In Table 1 there are given the characteristics of particle size distribution and in Table 2 washability characteristics - density-and quality - the same for all grain size classes.

In the jig model [5] for the three size fractions: 0.5-1 mm, 2-5 mm and 8-20 mm there are five generalized separation curves which have been shown in Fig. 1. The first two curves relate to the cleaning of particles in the class 0,5-1 mm (weighted value of Ep = 0.177), another two - in the class 2-5 mm (weighted value of Ep = 0.082), and the last curve - in the class 8-20 mm (Ep = 0.062). The shape of these distribution curves thus confirms the known effect of more precise cleaning of larger size grains.

Cleaning forecasts have been done for four technolog-

Tab. 1 Characteristics of raw coal particle size

Tab.1 Charakterystyka wielkości cząstek nieprzetworzonego węgla

Class number	Particle size (mm)	Size class fraction (%)
1	0,5 – 1	35
2	2 – 5	30
3	8 – 20	35

Tab. 2 Density-quality feed characteristics (0,5-20 mm)

Tab. 2 Charakterystyka gęstości nadawy (0,5-20 mm)

Fraction density (g/m^3)	Fraction output (%)	Ash content (%)	Total sulphur content (%)	Calorific value (kJ/kg)
< 1,30	12,15	4,67	0,84	30 680
1,30-1,35	17,96	7,40	0,86	29 630
1,35-1,40	10,95	10,99	0,97	27 300
1,40-1,50	8,47	17,92	1,10	25 750
1,50-1,60	7,43	26,61	1,24	22 550
1,60-1,70	7,02	35,81	1,25	19 160
1,70-1,80	3,95	43,81	1,13	16 220
1,80-1,90	4,04	51,03	1,12	13 560
1,90-2,00	2,57	57,08	1,39	11 330
> 2,00	25,45	75,84	2,75	4 420
Total	100,00	33,67	1,46	19 960

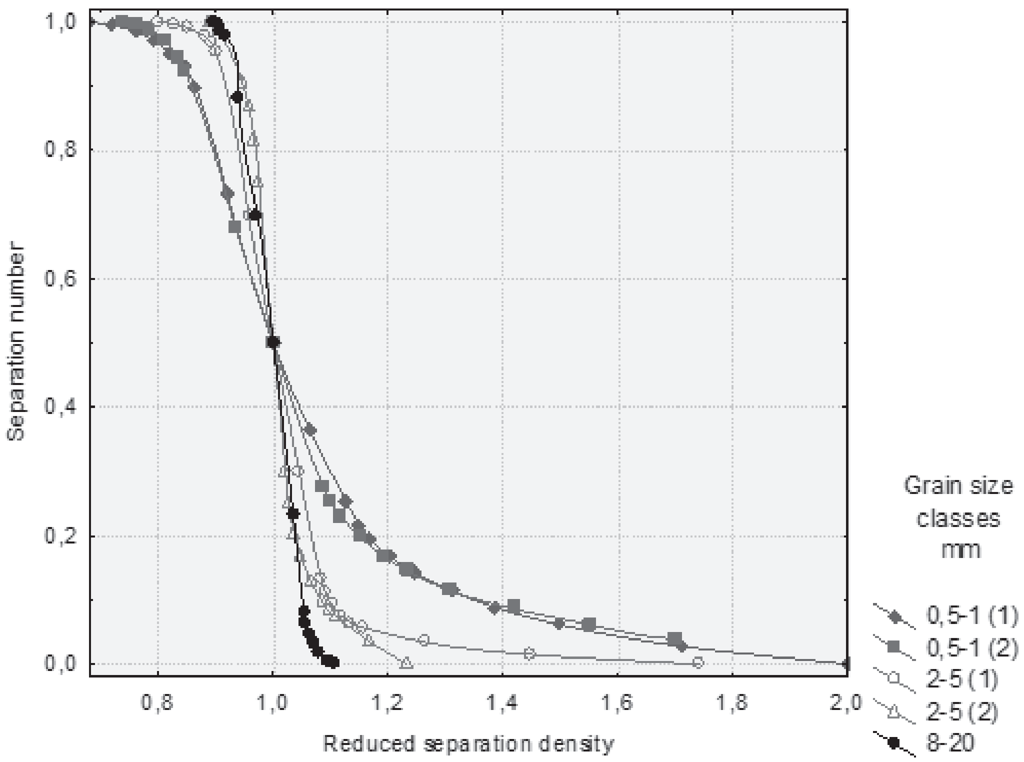


Fig. 1 Selected generalized separation curves of the two-product jig.

Fig. 1 Wybrane krzywe rozdziału dla dwuproduktowej osadzarki ical systems with layouts shown on Fig. 2.

In the first system (1 os.) coal is cleaned in a single jig, the next two systems (2 os. I and 2 os. II) are parallel coal cleaning layouts in two jigs which differ in the size of the screen openings. In 2-os. I system in the first jig there are cleaned particles are two finest size feed classes (1 and 2 in Table 1) and in the second jig the largest size class (class 3), and in 2-os. II system in the first jig there are cleaned only the finest grains (1) and in the other jig two other size classes (2 and 3). In the fourth system (3 os.) each size class is separately cleaned in three parallel jigs.

The production value at the desired concentrate quality

Simulation forecasts have been performed using simulation models of coal processing operations [5] described in [2, 3, 12]. The forecasts in the whole paper have been limited to two desired concentrate ash content values: 13 and 16%.

Maximizing production of the desired quality of the concentrate and constant composition of raw coal particle size distribution

In the optimizing calculations there has been used an algorithm to maximize the production of desired quality [2, 12]. For the production value calculations there has been used the 4-th version of the sales formula from 2002 [1].

Production value (*PV*), which is an objective function of the maximizing algorithm is defined in subsequent systems shown in Fig. 2 by one from the following relationships:

$$PV_i(\delta_{os1}) = M_{Ki}(\delta_{os1}) \cdot C_{Ki}(\delta_{os1}) \tag{1a}$$

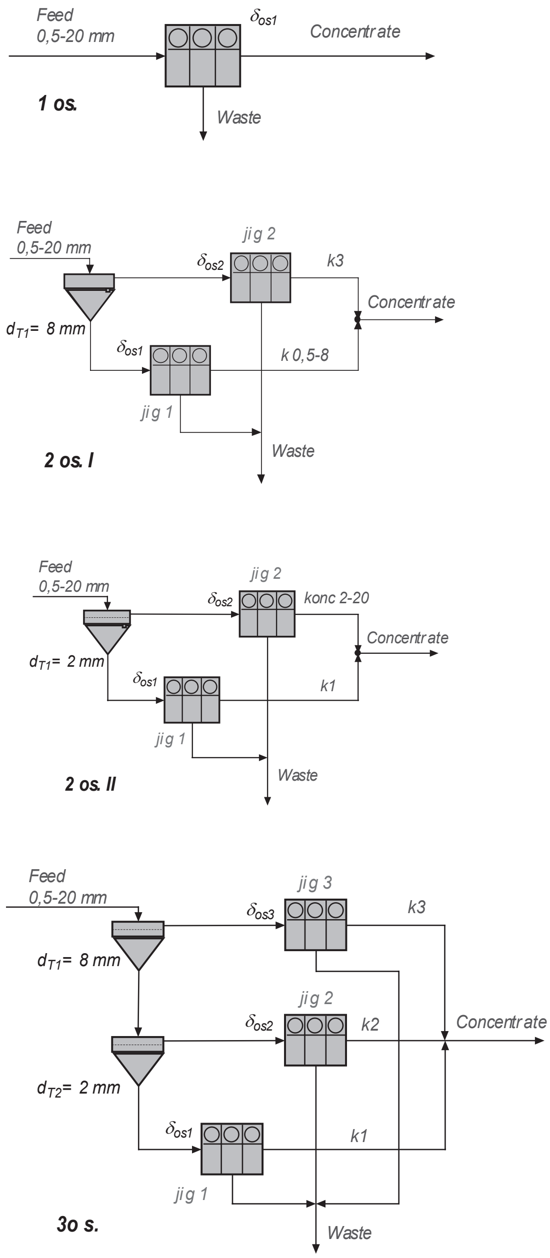


Fig. 2 Technological layouts of considered jig cleaning systems [10, 11]

Fig. 2 Schematy technologiczne omawianych systemów wzbogacania w osadzarce [10,11]

$$PV_i(\delta_{os1},\delta_{os2}) = M_{Ki}(\delta_{os1},\delta_{os2}) \cdot C_{Ki}(\delta_{os1},\delta_{os2}) \quad (1b)$$

$$PV_i(\delta_{os1},\ \delta_{os1},\ \delta_{os3}) = M_{Ki}(\delta_{os1},\ \delta_{os1},\ \delta_{os3}) \cdot C_{Ki}(\delta_{os1},\ \delta_{os1},\ \delta_{os3}) \quad (1c)$$

Therefore it is sought the maximum of PV_i (max PV_i) with a strong restriction of the ash content in the final concentrate:

$$A_K = A_{Ki}, \quad (2)$$

where:
δ_{os1}, δ_{os2}, δ_{os3} – separation densities in jigs, [g/cm^3]
M_K – concentrate mass, [Mg]
C_K – unit price of concentrate calculated from the sale formula, [zł/Mg]
A_K – concentrate ash content (A_{Ki} = 13% or A_{Ki} = 16%) [%]

Production value in systems with two or three jigs is always greater than in the single jig system at the same desired concentrate ash content [10, 12]. From the maximization of equation (1) there have been determined optimum separation densities for jigs in systems from Fig. 2. They have been shown in Table 3.

Coal cleaning at constant separation densities and varying particle size distribution

Raw coal washability, grain size composition and flow rate are characterized by a certain variability, due to various reasons. If the feed to the coal processing plant is stored in the buffer tank, then there is some averaging of quality parameters, but most of all, the flow rate can be stabilized. The impact of washability changes on the cleaning effects has been presented in different publications - in this paper there are described only forecasts of the impact of changes in the grain size composition, assuming invariant washability characteristics and constant flow rate [11, 12]. In order to trace the impact of changes in various size classes participation in the feed, the raw coal has been split into two feed streams N1 and N2 with different grain size composition, which is shown in Table 4, but with the same washability characteristics (Table 2).

The combination of N1 and N2 feed streams in the proportions of 50% results in the same characteristics of particle size distribution as in Table 1. It can be said that all calculation results presented above apply to such a case - combining N1 and N2 feed streams in identical proportions.

In the following calculations with results presented below, the total mass of both feed streams has always remained the same, changing only the quantitative shares of N1 and N2 feed streams respectively in the ranges: 0÷100% and 100÷0%. The increase in the N1 feed stream share (while reducing the N2 feed stream share) means that more largest particles (class 3) are cleaned precisely (with less inaccuracy Ep). It also means a smaller amount of ultrafine particles (class 1), cleaned with greater inaccuracy. The share of intermediate size particles (class 2) remained unchanged in each case. With an increase in the N1 feed stream share- and a simultaneous decrease in the N2 feed stream share – it can be said as the improving grain size composition in terms of the cleaning accuracy. Still the notion of particle size distribution change shall be described

Tab. 3 Optimum separation densities for jigs in systems from Fig. 2

Tab. 3 Optymalna gęstość rozdziału dla osadzarek przedstawionych na Rys. 2

Cleaning layout		optimum separation densities in jigs g/cm^3	
		A_k = 13%	A_k = 16%
1 os.	δ_{os1}	1,541	1,698
2 os. I	δ_{os1}	1,515	1,645
	δ_{os2}	1,635	1,829
2 os. II	δ_{os1}	1,477	1,597
	δ_{os2}	1,599	1,771
3 os.	δ_{os1}	1,475	1,603
	δ_{os2}	1,554	1,713
	δ_{os3}	1,658	1,823

Tab. 4 Characteristics of particle size distribution for N1 and N2 feed streams

Tab. 4 Charakterystyka rozkładu wielkości ziaren dla strumieni nadawy N1 i N2

Class number	Particle size (mm)	Class fraction (%)	
		N1	N2
1	0,5 – 1	0	70
2	2 – 5	30	30
3	8 – 20	70	0

as specific changes in N1 and N2 feed stream participation.

The calculations performed in the previous point (3.1) have determined optimum separation densities for jigs in different cleaning systems depicted in Fig. 2, for obtaining the maximum production value of the desired final concentrate quality in case of constant grain size distribution. With such a set of optimum jig separation densities there have been performed impact analyses of particle size distribution changes. The following figures shows the influence of changes in N1 and N2 feed stream participations on the concentrate ash content (Fig. 3), the yield (Fig. 4) and the production value (Fig. 5). All points with equal participation of both feed streams (50%) refer to the initial situation. Points located on the left side refer to worse, and on the right side to a better grain size composition - in terms defined above.

The concentrate ash content and the final yield of all systems decrease with the improvement of grain composition. The concentrate parameters least change in the layout with three jigs (3 os.) and most in a single jig system (1 os.). the single jig system is therefore the most sensitive one to changes in the grain size composition. Changes in ash content (and calorific value and sulfur content) have been taken into account when determining the concentrate unit price from the sales formula.

Fig. 5 shows the change in the production value, calculated according to the equation (1a) - (1c) and related to the production value obtained from a single jig with equal N1 and N2 feed stream participation (50%).

From Fig. 5 it follows that the improvement of particle size composition at a constant separation densities (for obtaining the concentrate ash content of 13% or 16%, with equal N1 and N2 feed stream shares) results in an increase of the production value in systems with parallel cleaning in three jigs. In systems with two jigs increase in the value of production holds for A_{Kzad} = 16% (Fig. 5b); but for the A_{Kzad} = 13% the production value slightly decreases. In a system with a single jig, the production value is significant-

a)

b)

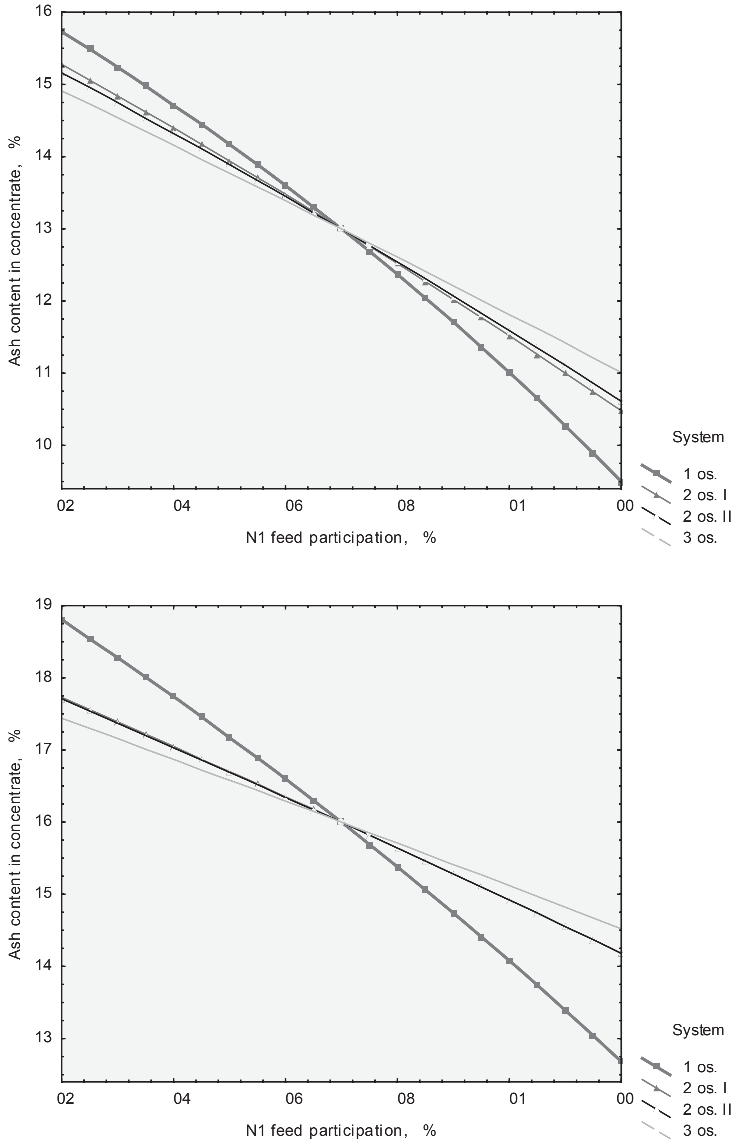


Fig. 3 Concentrate ash content for systems from Fig. 2 at different N1 and N2 feed stream participation: a) *Azad* = 13%, b) *Azad* = 16%

Fig. 3 Zawartość popiołu w koncentracie dla układów z Rys. 2 w strumieniach nadawy N1 i N2: a) *Azad* = 13%, b) *Azad* = 16%

ly reduced. This very negative effect is due to the fact that at the high concentrate quality separation densities are relatively small - concentrate price increase resulting from the improvement of its quality (Fig. 3), does not compensate for the yield decrease (Fig. 4) [11, 12].

Maximizing production of the desired quality of the concentrate and varying composition of raw coal particle size distribution

With the change of particle size composition changes there was re-used algorithm to maximize production value. For each combination of N1 and N2 feed streams there were determined optimum separation densities (Fig. 6) for each cleaning systems and two desired values of the concentrate ash content: 13 and 16%.

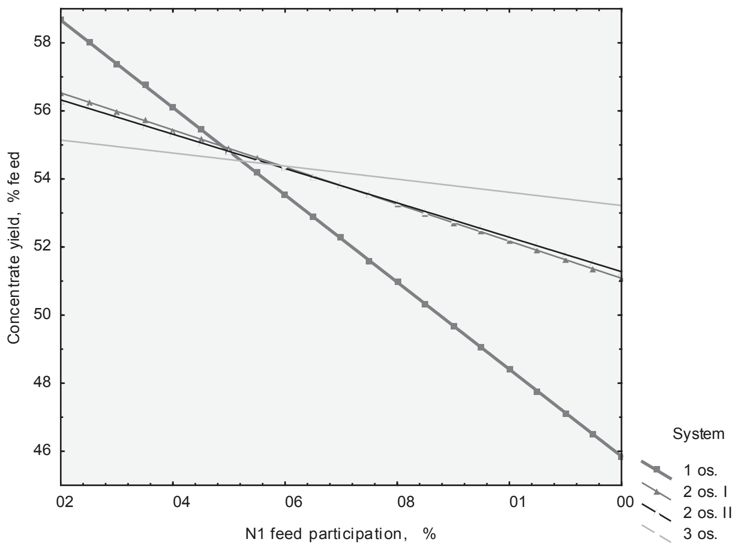
Application of on-line video analysis of feed particle size distribution feed to jig cleaning systems

In currently used coal cleaning solutions concentrate quality is determined by on-line measuring the ash content in the concentrate. Because the jig cleaning process is sensitive to changes in raw coal grain size composition (Figs. 3-5), it is desirable to provide a fast reaction of jig control system to these changes. Concentrate ash content measurement provides obviously meaningful information for the calculation of the separation density changes, but this information is delayed by a few minutes because of transport delays of cleaned material throughout jigs and screens. For this reason, the use of on-line video analysis of feed particle size distribution enables faster for a few minutes, reaction of the jig control system to changes in grain size composition

General characteristics of the on-line visual analysis of feed particle size distribution

Fig. 7 shows a concept of controlling the jigs using both the measurement of ash content in the concentrate,

a)



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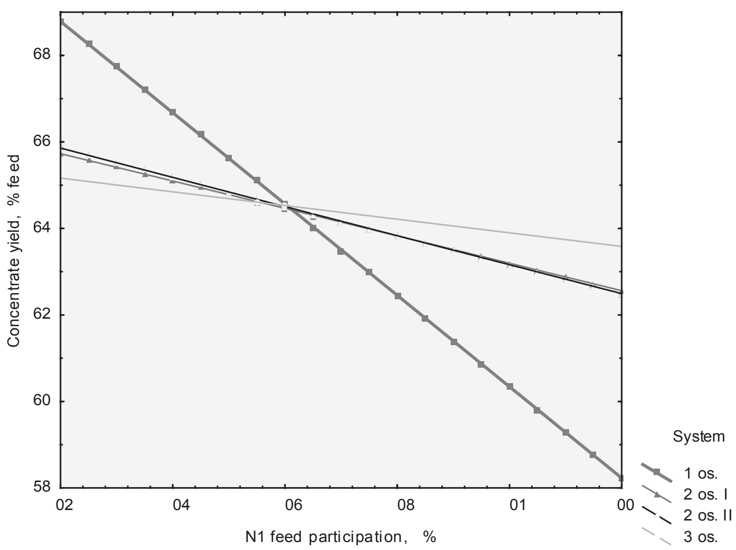


Fig. 4 Concentrate yield at different N1 and N2 feed stream participation: a) *Azad* = 13%, b) *Azad* = 16%

Rys. 5 Wychód koncentratu dla różnych wielkości nadawy N1 i N2: a) *Azad* = 13%, b) *Azad* = 16%

and the video analysis of the feed grain size composition, so it is a complex optimal control system [13].

Video analysis of particle size distribution by its nature is not a continuous process, but a time-discrete one [7,8] (statistical analysis is performed for a grain size composition sample within a defined area - that can be made only after completion of the acquisition of the entire two-dimensional or three-dimensional image of the conveyor belt section), however, the data acquisition time and the time of these data subsequent processing is much shorter than the other delays and time constants associated with the ongoing process of gravitational coal cleaning. For this reason, it can be measured a significantly larger portion of the feed than with the traditional sieve analysis and the results of such a measurement can be used not only for control and diagnostic (ie. detection of possible feed disturbance), but also for direct control of technological processes [9], in fast response to these input feed grain size composition disturbances. Video measuring systems due to the lack of direct contact with the measured process possess a high degree of reliability, especially in harsh environmental conditions [6].

As mentioned above, the use of on-line video analysis of feed particle size distribution enables faster by a few minutes the reaction control systems to changes in grain composition. The result is the production of more time-stable quality (ash content) concentrates, and there are possible cases possible to increase the production value. In p. 4.2 there are presented estimates of the extent to which the on-line analysis of particle size distribution of the feed to the one jig or and 2 and 3 jigs operating in parallel (Fig. 2) can improve the cleaning efficiency, determined by the increase in the production value relative to the system without such an analysis.

The increase in production value with the on-line analysis of particle size distribution in the case of grain size composition disturbances – assessment of the economic

a)

b)

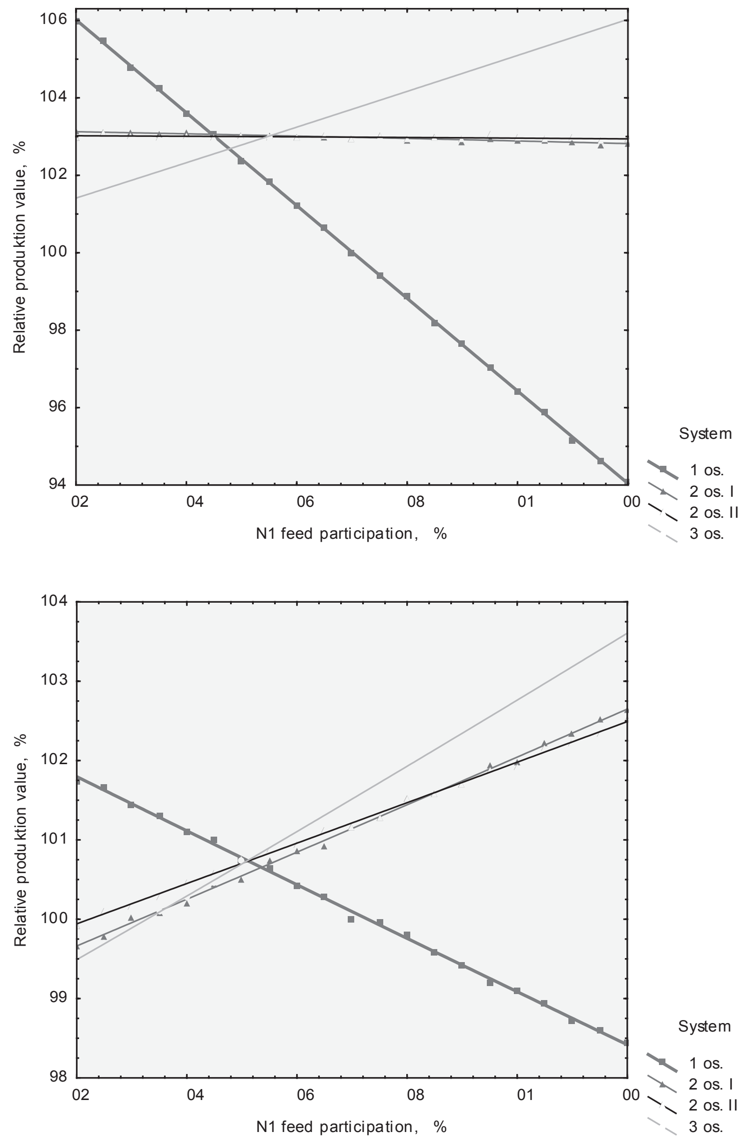


Fig. 5 Production value for different N1 and N2 feed stream participation: a) *Azad* = 13%, b) *Azad* = 16%

Fig. 5 Wartość produkcji dla różnych wielkości nadawy N1 i N2: a) *Azad* = 13%, b) *Azad* = 16%

efficiency

In order to estimate the economic advantages of the use of on-line video analysis of feed particle size distribution to control jigs and to compensate for the grain size composition disturbances there have been made several simplifying assumptions, namely:

- the time horizon of the production value analyses is equal to 1 hour of cleaning system operation according to Fig. 2,
- jig productivity equals 400 Mg/hr.,
- equal (50%) shares of both N1 and N2 feed streams determine the initial position at which should operate considered cleaning systems,
- unequal N1 and N2 feed stream shares are the disturbances of grain size; it is assumed that the disturbance duration is equal to 5 minutes (during this time period two N1 and N2 feed shares are fixed, but different from 50%),
- cleaned coal transport delay throughout the jig is 2 minutes, and throughout the screen equals to 1 minute,
- there are not considered cases of any contractual penalties as a result of worse than contracted concentrate quality or financial losses resulting from a fixed contract price of better then contracted concentrate quality,
- washability characteristics - density-quality – are the same for all grain size classes.

The occurrence of feed particle size disturbances results in different concentrate output and - in the case when the separation densities does not have the optimum values – different quality. In a system with an on-line analysis of particle size distribution it has been assumed that feed particle size disturbances are detected by video analysis system, so the control system controls the jigs operation such that the resulting optimum (for respective N1 and N2 feed streams) separation densities are obtained. With such control the desired concentrate ash content is achieved even during the disturbance period. Traditional control system can response to grain size disturbances only after the out-

a)

b)

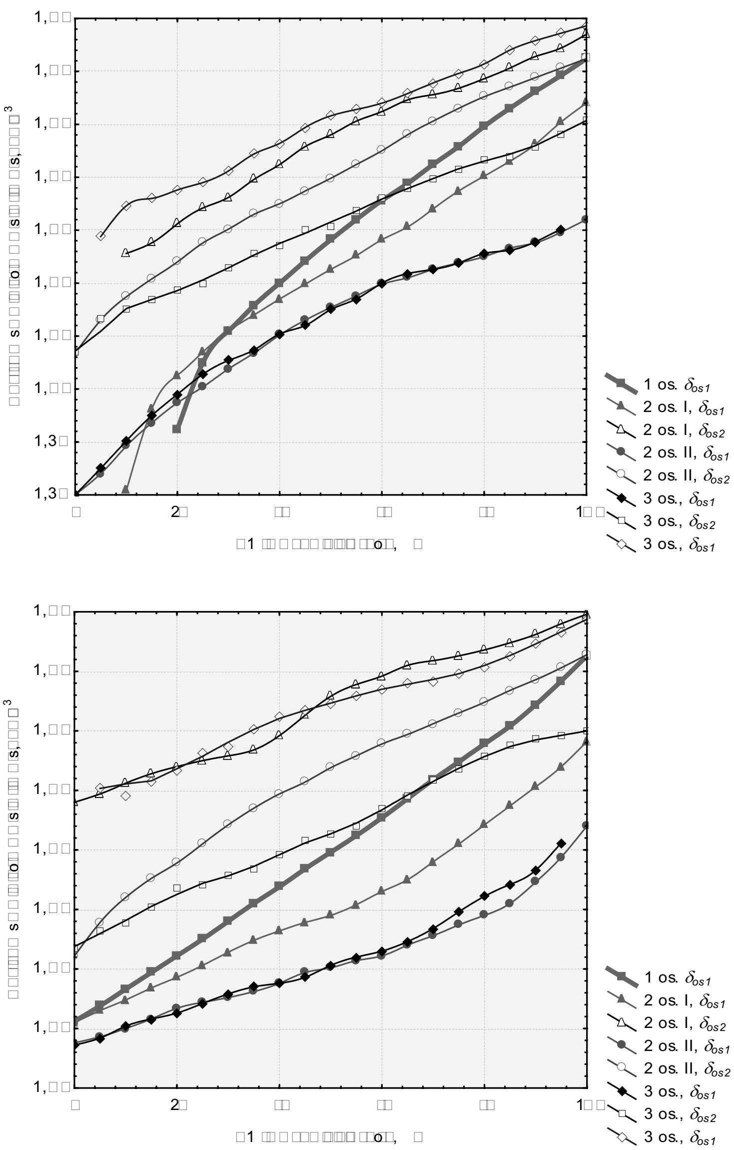


Fig. 6 Optimum jig separation densities for different N1 and N2 feed stream participation: a) *Azad* = 13%, b) *Azad* = 16%

Rys. 6 Optymalna gęstość rozdziału w osadzarce dla różnych strumieni zasilających N1 i N2: a) *Azad* = 13%, b) *Azad* = 16%

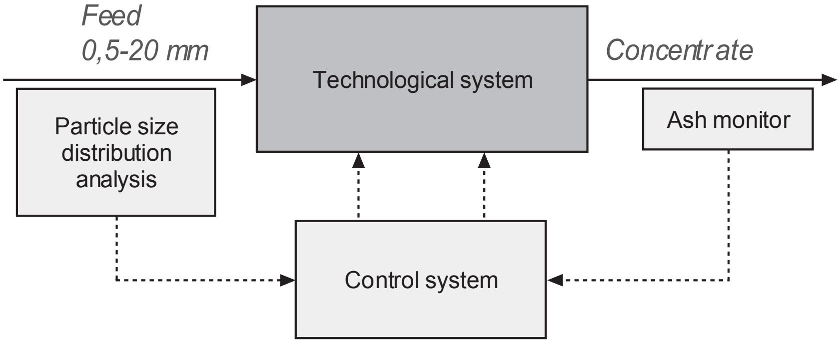
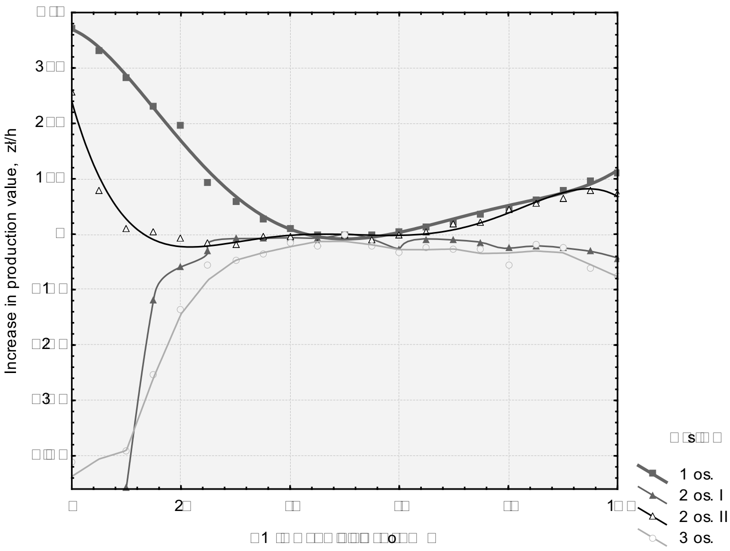


Fig. 7 Application of the on-line analysis of particle size distribution to jig cleaning control system

Rys. 7 Zastosowanie analizy *on-line* rozkładu wielkości ziaren nadawy do układu wzbogacania

a)



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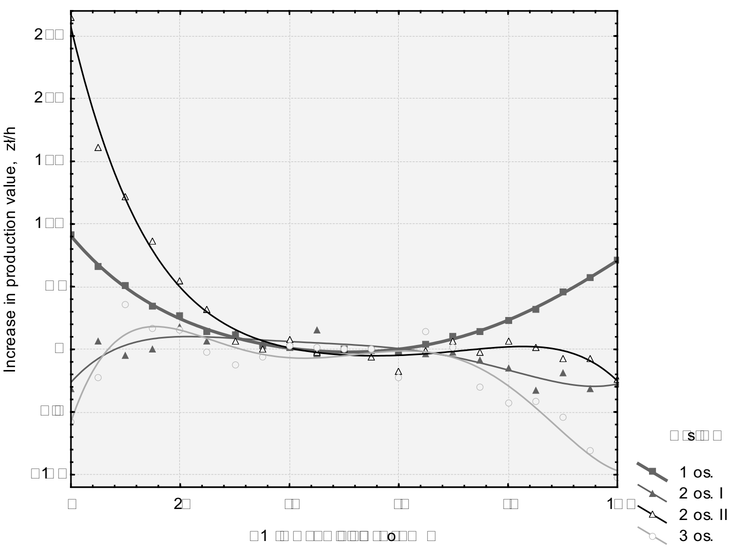


Fig. 8 Increase in production value in a system with on-line video particle size composition analysis at one disturbance per hour: a) Azad = 13%, b) Azad = 16%

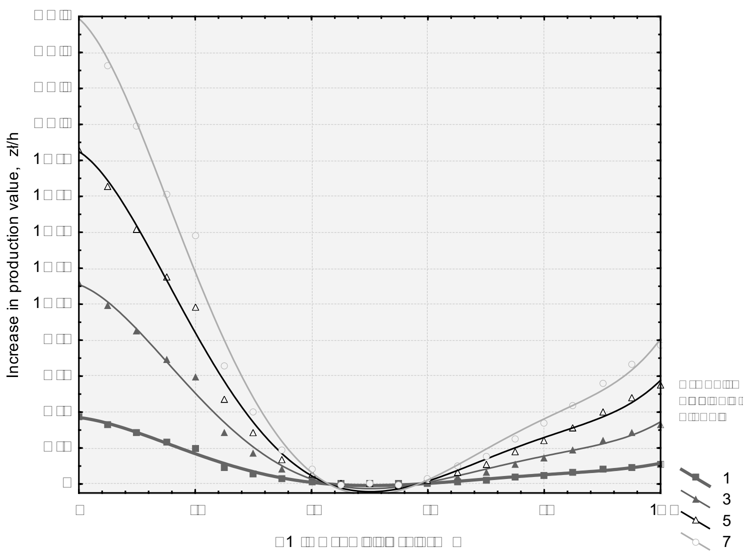
Rys. 8 Wzrost wartości produkcji w systemie z analiza on-line wielkości ziaren z jednym zakłóceniem na godzinę: a) *Azad* = 13%, b) *Azad* = 16%

put ash monitor detects different (than desired) concentrate ash content. There is a significant impact of delay time resulting from transportation of cleaned coal through jigs and screens (in systems with two or three jigs). The occurrence of disturbances causes sub-optimal cleaning for 2 (single jig) or 3 minutes (parallel cleaning systems). Only after this time, the jig can operate with optimum densities section (Fig. 6). Also, the end of the disturbance and return to the initial situation (equal N1 and N2 feed stream shares) means that for 2 or 3 minutes cleaning is not optimal, in the sense of obtaining desired concentrate quality. The result of these delays can be - and frequently is - concentrate quality different from the desired value.

First, it was assumed that within one hour of operation there is only one five-minute disturbance of raw coal particle size distribution. Computationally this has been done in such a way that for the system with video analysis for 55 minutes N1 and N2 feed shares equal to 50% and the cleaning is carried out at optimum separation densities (p. 3.1, Table 3). The remaining 5 minutes when there is a grain size disturbance detected by the video analysis, separation densities are the same as in Fig. 6, depending on the N1 and N2 feed stream participation. For such defined two time periods there are separately determined qualitative and quantitative concentrate parameters. In the case where there is no on-line analysis of particle size distribution, five-minute disturbance of grain composition is modeled by three time intervals: 2 or 3 minutes non-optimal operation (density distribution as in Tab. 3), 3 or 2 minutes optimum performance (density distribution as Fig. 6), and - after the disturbance end - another 2 or 3 minutes non-optimal operation.

The remaining 53 (single jig) or 52 minutes (cleaning

a)



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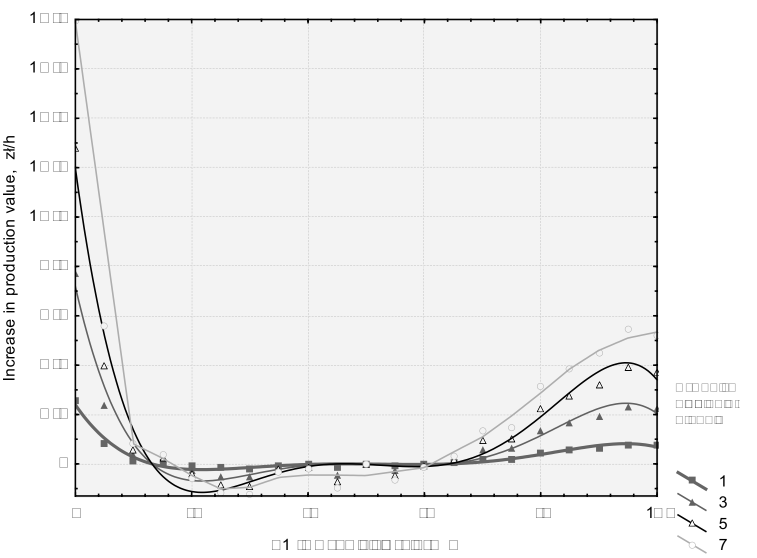

Fig. 9 Increase in production value in a system with on-line video particle size composition analysis at more disturbancse per hour: a)1 os., b) 2 os. II

Rys. 9 Wzrost wartości produkcji w systemie z analizą on-line wielkości ziaren z więcej niż jednym zakłóceniem na godzinę: a)1 os., b) 2 os. II systems with two or three jigs) the cleaning is performed at the optimum separation densities when both the N1 and N2 feed stream participation equals to 50% (Tab. 3). Qualitative and quantitative concentrate parameters are determined separately for these four time intervals.

With these calculated – individually for these two or four time intervals- concentrate parameters, the resultant concentrate weight is determined by summing up the partial weights, and all the qualitative parameters are determined using the weighted average.

From the data obtained, it can be determined the production value during the one operation hour, as the product of the concentrate mass and price, similarly as in the equations (1a) - (1c). Fig. 8 shows the differences in the production value (treated as an increase in production value) derived for systems with video analysis of particle size analysis, and without these analysis, at one five-minute disturbance during an operation hour. In a system with one jig, control with the grain-size analysis almost always brings a positive economic effect. In other systems (with two or three jigs) also there are possible situations when there is an increase in production value. It should be noted that even if this increase (Fig. 8) is negative, it is generally connected to obtaining another (than desired) production quality in the system without video analysis of particle size distribution.

Subsequently, it was assumed that during 1 hour there can be more five-minute disturbances. Results in Fig. 9 are limited only to illustrate the production value increase in a system with one jig (1 os.) and with two jigs (2 os. II) at a given concentrate ash content of 13%. There can be also seen significant economic benefits arising from the application of video particle size analysis to enhance jig control.

Conclusions

The coal cleaning process in the jig is sensitive to changes in the feed grain size composition. Since smaller grains are cleaned with lower precision than larger grains (which can be seen on the shapes of separation curves - Fig. 1), therefore the changes of various size grain shares lead to obtaining concentrates of various quantitative and qualitative parameters (Fig. 3 and 4) and different production values (Fig. 5). The most sensitive to changes in grain composition system is a technological layout with one jig, the least sensitive system is a layout with three jigs.

Improvement of grain size (understood as the increase in the proportion of larger grains, cleaned with greater precision) generally results in an increased production value (Fig. 5) in parallel cleaning systems, and causes a decrease in the production value in the system with one jig [11,12]. The use of video analysis of particle size enables faster by a few minutes the reaction of jig control systems to changes in grain composition, resulting in the production of concentrates with more time-stable qualitative parameters. This may lead to an increase in the production value. Even if the production value is reduced as compared to the system without video analysis, it must be remembered that in this solution (without video analysis) obtained concentrate quality deviates from the reference value. The paper does not take into account cases of any contractual penalties as a result of lower than contracted concentrate quality, or financial losses resulting from a fixed contract price in the case of better quality concentrate.

From described above analyses of the increase in the production value in the solution with on-line video analysis of feed grain size composition it is possible to state that costs of installing appropriate equipment can return in a very short time of a few days.

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Ekonomiczna ocena efektywności zastosowania analizy on-line wielkości ziaren nadawy w układach wzbogacania w osadzarkach węglowych

W obecnie istniejących zakładach wzbogacania węgla jakość węgla jest oceniania przez analizatory on-line zawartości popiołu. Proces wzbogacania w osadzarce jest wrażliwy na uziarnienie nadawy. Z tego powodu analiza video on-line rozkładu wielkości ziaren pozwala na szybszą (do kilku minut) reakcję systemu kontroli na zmiany wielkości ziaren, co w konsekwencji prowadzi do bardziej skoncentrowanej produkcji ze stabilniejszymi parametrami jakości (zawartości popiołu). Ostatecznie może to prowadzić do zwiększenia wartości produkcji. W artykule podjęto próbę oceny stopnia polepszenia się wydajności wzbogacania z wykorzystaniem analizy on-line wielkości ziaren nadawy dla jednej, dwu lub trzech osadzarek.

Słowa kluczowe: analiza skladu ziarnowego, osadzarka, wzbogacanie węgla, efektywność ekonomiczna