JOACHIM PIELOT
WOJCIECH PIELUCHA

Analysis of effects of coal enrichment in jigs at changing grain composition of the feed

One of the basic coal preparation processes is coal preparation in water pulsating jigs. The efficiency of coal preparation depends on the washability of the raw coal feed and the shape of partition curves which, in turn, depend on the grain composition of the feed. Thus, when the grain composition changes, it is necessary to change the partition density of the jig (by changing the reception intensity of the undersized product) [2, 6]. The authors of the article attempted to estimate, tentatively, how an on-line analysis of the feed grain composition, in technological configurations with one or two jigs that successively prepare the concentrates, can improve the preparation efficiency with respect to the dynamic properties of the jig. The jig is an inertial object with time delay – transport delay. However, preparation processes of minerals have a non-linear character [4, 12] – equivalent parameters of the object are different for positive and negative changes in the set value. Dynamic effects of preparation were presented with respect to changes in the grain composition.

Keywords: *coal enrichment in jigs, grain composition of coal, on-line control, control dynamics.*

1. INTRODUCTION

A coal preparation process results in different volumes and quality of products, depending on the grain composition and washability of raw coal, type of preparation operations in the coal preparation technological configuration, partition parameters of these operations, and the degree of the preparation inaccuracy. The inaccuracy of preparation is caused by a non-ideal quality of the process which results in a non-ideal shape of partition curves [7, 15] used for modelling preparation processes in gravity concentrators. The shape of the partition curves is influenced by the size of grains in jigs – the smaller are the grains, the worse is the shape of the curves as it differs more from the ideal shape. This situation results in higher inaccuracy of the enrichment process. The shape of partition curves has a direct impact on the volume and quality of concentrates.

The article is a continuation of the work [1] and, simultaneously, preliminary research on the impact of dynamic properties of jigs on preparation effects in the conditions of the changing grain composition of the feed. Dynamic effects of preparation were compared. In addition, the reaction of the preparation system was assessed with respect to control changes in the case of simulated changes of the grain composition of raw coal. Further, more diverse cases of the grain composition changes in different technological configurations will be taken into account. The objective of the works undertaken by the Department of Electrical Engineering and Control in Mining is visual on-line identification of changes in the grain composition [8, 9]. This way it will be possible to force partition density changes in direct control systems (with the use of optimization layers, supervisory control [16] and adaptive regulation algorithms. The changes will be forced in such a way that the quality of the concentrate will be stabilized, which should result in a higher production value.

2. ANALYZED TECHNOLOGICAL CONFIGURATIONS

The work [10] features the influence of grain composition changes on enrichment effects in a single jig and in parallel enrichment configurations of two and three jigs. While [1] presents the effects in two configurations of successive enrichment in two and three jigs, in which temporary concentrates are prepared again, as well as in a configuration with the temporary product recirculation. The presented analyses referred to static states only and did not take into account temporary states during control changes in the configuration. Here the authors presented the impact of grain composition changes on selected control quality indicators at the PI controller settings selected by means of two methods.

Figure 1 features two technological configurations to which preparation and control prognoses refer. The considered configuration with one jig (*1 os.*) is treated as a reference configuration (similarly to [1, 10, 15]); the second configuration is a configuration for successive preparation in two jigs (*2 os.*).

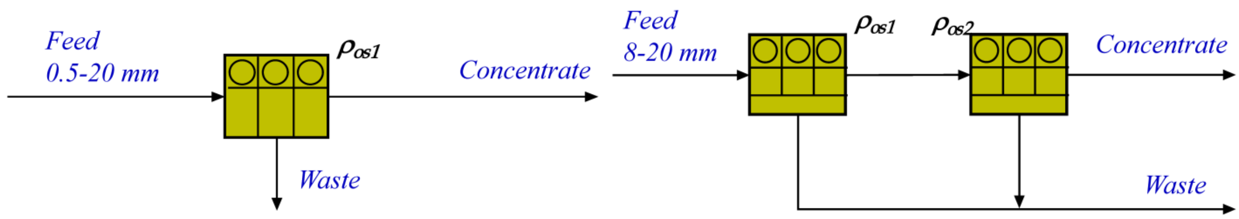

Fig. 1 Analyzed preparation configurations

Nowadays the concentrate quality is determined by on-line measurement of ash content and the result of this measurement is used to correct the partition density – this is the basic method to stabilize the concentrate quality. Partition density is understood as the fraction density of the enriched coal, passing one half to the concentrate and the other half to the waste.

As for the enrichment process in jigs, the term of partition density is a theoretical one. The basic parameter which impacts the partition density in a jig is the flow efficiency of the undersized product [3]. Instead of the partition density it is necessary to determine the density of the partition layer of enriched products [4]. In practical applications the position of the layer of the set-density material is determined by means of a float which is a sensor in the control system of the undersized product reception. In the latest systems for controlling jigs operations an isotope density meter is installed in the enriched-products reception zone. The meter is used to correct measurement errors of the float when the jig operations are unstable [3]. Still, due to the character of this paper whose objective is to present potential effects of control with the use of the on-line analysis of grain composition, it is justifiable to use the theoretical term of partition density[1].

Figure 2 features a block diagram with a control system of one jig or two jigs that successively enrich the concentrates. The visual analysis system provides information about the current grain composition of the feed [8, 9]. In the supervisory control system the optimal partition density ρ_{opt} (dependent on the grain composition) is selected for the set ash content in the concentrate. At the same time, based on the measurement of ash content in the concentrate Ak, the controller changes the flow efficiency of the undersized product. This operation results in a changed value of the partition density in one jig or two jigs. It is important to note that in successive enrichment systems of two (or three) concentrators the optimal partition density values in particular concentrators are always identical. Thanks to this, the enrichment inaccuracy takes its minimal value, while the shape of partition curves is as close to the ideal one as possible [15].

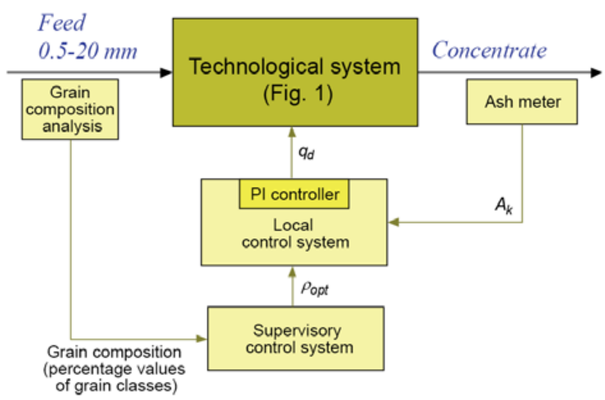

Fig. 2. Block diagram of a control system for one of two jigs (as in Fig. 1)

Taking into consideration the on-line analysis of a feed grain composition whould cause a much faster reaction of a control systems, even few minutes faster when compared to the basic way – only with the usage of an ashmeter. As an effect of faster control changes the final concentrates quality parameters

[1] In the case of possible practical applications with the use of the analysis system of grain composition, the partition density will be replaced by the partition layer density of enriched products or some research will be conducted about the correlation between these quantities.

should become more stable, what shold influence the increase of the product value.

The characteristics of low- washability raw coal were adopted for simulation calculations. Table 1 features the characteristics of the grain composition, while Table 2 – washability characteristics, i.e. density- and quality-based washability, the same for all grain classes.

Table 1
Characteristics of feed grain composition of raw coal

Class number	Grain sizes mm	Percentage values of feed grain classes %
1	0.5 – 1	35
2	2 – 5	30
3	8 – 20	35

Table 2
Density and quality characteristics of the feed (0.5-20 mm)

Fraction density g/cm^3	Fraction yield %	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
Razem	100.00	33.67	1.46	19,960

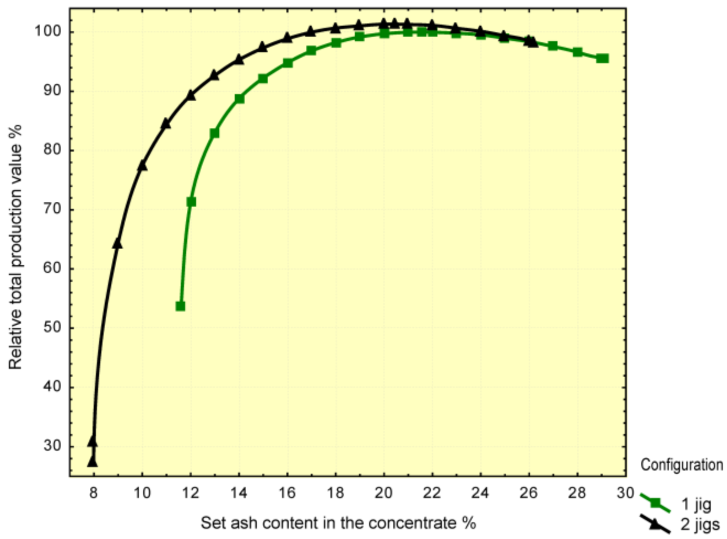

Fig. 3. Relative maximal value of the final concentrate production for the whole achievable range of ash content

3. COMPARATIVE ANALYSIS OF ENRICHMENT EFFECTS

For the purpose of a jig coal enrichment effects forecasting, diferent models of separation curves (identified for different grain classes) were used [7]. Figure 3 presents maximal, achievable production values in the conditions of a stable grain composition of the feed, at different set qualities of concentrates [1, 15]. In optimization calculations the production maximization algorithm of the set quality was applied [15]. The configuration with one jig is a reference configuration, therefore the maximal production value that can be achieved in this configuration has the relative value of 100% assigned.

3.1. Changes in grain composition of raw coal

The washability, grain composition and flow efficiency of raw coal are variable parameters. If the feed, which is to be delivered to the coal preparation plant, is in the buffer container, the flow intensity is stabilized and quality parameters are somehow averaged. The article gives the prognoses how the changes impact only the grain composition, at the assumption that washability and constant intensity characteristics are unchanged [13, 14]. It was assumed that the changes in the grain composition are based on changes in the shares of particular grain classes in raw coal. For this reason, the feed was divided into two feeds, N1 and N2, with different grain compositions (Table 3) but the same washability characteristics (Table 2).

Table 3
Characteristics of grain composition of N1 and N2 feeds

Class number	Grain sizes mm	Percentage values of the feed grain classes %	
		N1	N2
1	0.5 – 1	0	70
2	2 – 5	30	30
3	8 – 20	70	0

In order to examine the impact of the grain composition changes it was assumed that the feed consists of two feeds, N1 and N2 (Table 3). These two feeds are always mixed in such proportions that their total share is equal to 100% [1, 15]. The increase in the N1 share from 0% to 100% results in simultaneously decreasing share of N2 from 100% to 0%. If the shares of both feeds are 50%, the shares of all three grain composition classes are approximately the same – such as in Table 1. This case reflects the initial situation and is treated as enrichment with undisturbed grain composition. As the washability characteristics are the same for all grain composition classes (Table 2), the changes of N1 and N2 shares result in changes of the grain composition only, not in the washability curves [1].

The results of all above mentioned simulation prognoses were achieved at a constant total weight of both feeds but at changing volumes of shares of N1 and N2. The increase in the N1 share (with the simultaneous decrease of the N2 share) results in a larger volume of the biggest, more thoroughly prepared grains (class 3) and, at the same time, a smaller volume of the finest grains (class 1) which are prepared with less accuracy. The share of medium-size grains (class 2) remained unchanged in all cases. With the increasing share of N1 and the decreasing one of N2, it is possible to observe improvement in the grain composition of the feed, meaning that the enrichment accuracy is better. Further in the article, the changes of the grain composition should be understood as the changes of mutual shares of the N1 and N2 feeds [1].

Figure 4 illustrates the impact of the N1 and N2 feeds shares on the ash content in the concentrate at unchanged, optimum partition densities adopted for equal shares of N1 and N2 (with no disturbances in the grain composition), at the set ash content in the concentrate equal to 13%. The changes in the N1 share within the range 0÷100% result in simultaneous changes of the N2 share in the range 100÷0%.

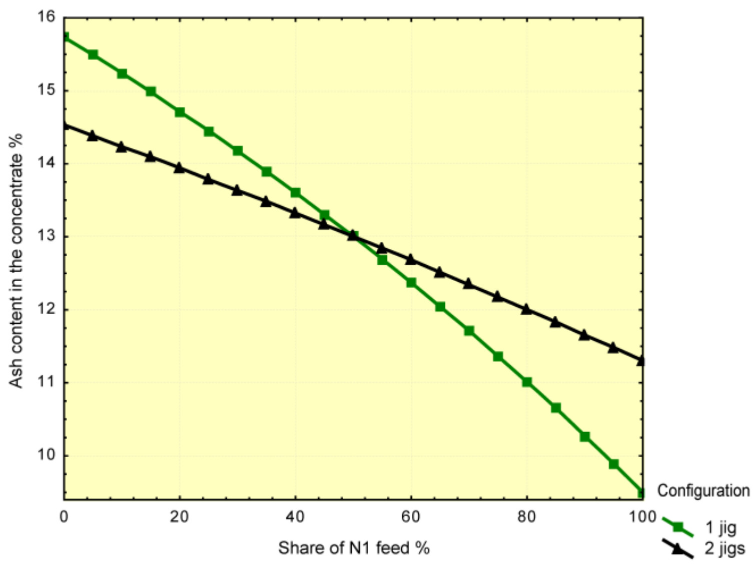

Fig. 4. Ash content in the concentrate according to configurations from Fig. 1, at different proportions of N1 and N2 feeds; A_{zad} *= 13%*

3.2. Comparison of dynamic effects of preparation at changes of grain composition

In technological systems for hard coal preparation the quality of the concentrate is determined by means of on-line measurements of ash content in the concentrate. As the enrichment process conducted in a jig is sensitive to changes in the raw coal grain composition (Fig. 4), it is recommended to have a quick reaction of jig operations control systems to these changes. Certainly, the result of ash content measurement in the concentrate is a reliable information to work out the partition density changes. However, the information is delayed by a few minutes due to the transport time of the prepared material in jigs and on screens. Therefore, the use of the on-line analysis of the feed to be prepared enables the control systems to react a few minutes more quickly, to the changes in the grain composition. The increasing production values determined in the works [1, 10] refer to the comparison of the production value in the systems without the grain composition analysis with those that employ on-line analysis of the grain composition. These results were achieved for static states, with respect to the transport time of prepared coal in one jig (2 min), but excluding the inertia of the jigs and control systems.

In order to make a comparative analysis of dynamic effects of enrichment, a jig model was adopted as an inertial object with time delay, described in [2, 19]. The object parameters for positive (increasing share of the N1 feed) and negative (decreasing share of the N2 feed) changes of the input signal were selected on the basis of the work [5]. The comparison concerned the effects of control systems operation in technological configurations with one or two jigs.

The adopted control algorithm was the increasing PI controller, described by the following formulas:

$$u[n] = u[n-1] + \Delta u[n]$$ (1**Błąd! Nie zdefiniowano zakładki.**)

$$\Delta u[n] = k_p \left\{ e[n] - e[n-1] + \frac{T_s}{T_i} e[n] \right\}$$ (2**Błąd! Nie zdefiniowano zakładki.**)

where:

u – control signal,
e – control error,
k_p – controller gain,
T_s – sampling period, T_s=1 s
T_i – controller integration time.

In both technological configurations the authors adopted the grain composition changes expressed as percentage shares of two feeds, N1 and N2, with different grain compositions – presented in Table 4.

The reaction to the changes in the feed grain composition should come from control systems (optimization layers, supervisory control and direct control [16, 18]) and, as a result of that, these systems should enforce proper changes in the partition density.

Table 4
Changes in the feed grain composition

No	Feed shares	
	N1	N2
1.	50%→75%	50%→25%
2.	50%→100%	50%→0%
3.	25%→50%	75%→50%
4.	100%→50%	50%→100%
5.	75%→50%	25%→50%
6.	50%→25%	50%→75%

It was assumed that ash content in concentrates from both technological configurations A_k=13 %. Using the production maximization algorithm of the set quality [15], optimal partition densities in the jigs were determined, at different shares of the N1 and N2 feeds. The changes in partition density, necessary to re-achieve the set ash content in concentrates (13%), are presented in Table 5 (for the configuration with one jig) and in Table 6 (for the configuration with two jigs).

Table 5
Required changes in partition density in a one-jig configuration

Change of grain composition (like in Table 4)	ρ_{os1} g/cm^3
1.	1.541→1.630
2.	1.541→1.710
3.	1.425→1.541
4.	1.710→1.541
5.	1.630→1.541
6.	1.541→1.425

Table 6
Required changes in partition density in a two-jig configuration

Change of grain composition (like in Table 4)	ρ_{os1} g/cm^3	ρ_{os2} g/cm^3
1.	1.701→1.739	1.700→1.739
2.	1.701→1.779	1.700→1.779
3.	1.664→1.701	1.663→1.700
4.	1.779→1.701	1.779→1.700
5.	1.739→1.701	1.739→1.700
6.	1.701→1.664	1.700→1.663

For the given partition density changes, the controller settings were adopted according to two methods:

A. direct method with the condition of the phase margin, described in [11];

B. modified method, in which the gain of the controller is bigger by a half and simulations are re-calculated for the same changes in the grain composition.

Based on the achieved flows, the control quality indicators were determined, described in the standard [17]:

– setting (control) time;
– rise time
– integral square error (ISE).

Table 7 features the values of the controller settings and the three above mentioned control quality indicators in both analyzed configurations, with the use of the A and B methods. The reference value (100%) corresponds to the integral square error (ISE) for the case when the share of the N1 feed increases from 50% to 100% in the configuration with one jig.

Figures 5 and 6 present relative values of the integral square error for a change in the grain composition. Figure 3 illustrates the values for N1 changing from 50% to 100%, while Figure 6 – for the same feed changing from 100% to 50%.

Table 7

Settings and control quality indicators for the considered configurations

Change of grain composition (like in Table 4)	Configuration	k_p	T_i s	Control time s	Rise time s	ISE %
Settings adopted according to the adoption method A						
1.	1 jig	195	30	194	70	117
1.	2 jigs	195	30	380	140	43
2.	1 jig	195	30	200	71	100
2.	2 jigs	195	30	388	140	43
3.	1 jig	195	30	196	71	199
3.	2 jigs	195	30	384	140	43
4.	1 jig	208	10	26	8	85
4.	2 jigs	208	10	52	16	36
5.	1 jig	208	10	25	7	99
5.	2 jigs	208	10	52	16	36
6.	1 jig	208	10	26	8	167
6.	2 jigs	208	10	52	16	36
Modified settings –method B						
1.	1 jig	292,5	30	230	32	96
1.	2 jigs	292,5	30	376	82	35
2.	1 jig	292,5	30	247	47	75
2.	2 jigs	292,5	30	374	82	35
3.	1 jig	292,5	30	235	34	96
3.	2 jigs	292,5	30	374	82	35
4.	1 jig	312	10	42	4	82
4.	2 jigs	312	10	48	10	35
5.	1 jig	312	10	43	5	96
5.	2 jigs	312	10	48	12	35
6.	1 jig	312	10	42	5	163
6.	2 jigs	312	10	48	10	35

4. CONCLUSIONS

Based on the conducted simulation analyses it can be concluded that:

– better enrichment effects are achieved with the configuration of two jigs which prepare the material successively;
– control time indicators in the configuration with two jigs have higher values than in the case with one jig; this is caused by the use of two machines with similar parameters, resulting in longer time of the preparation process;
– the value of the integral square error for the changes in the set density partition is significantly lower for two jigs than for one jig;

– the described modification of the controller settings (method B) causes slight increase of control time but, at the same time, shorter rise time; the value of the integral square error decreases significantly only in case of positive changes in the set partition density;
– the presented results allow to undertake work on determining how the changes in the feed grain composition impact the dynamic parameters of a jig and a set of jigs as control objects; at the same time, they allow to start working on the preparation of an adaptive algorithm for pulsating jigs control.

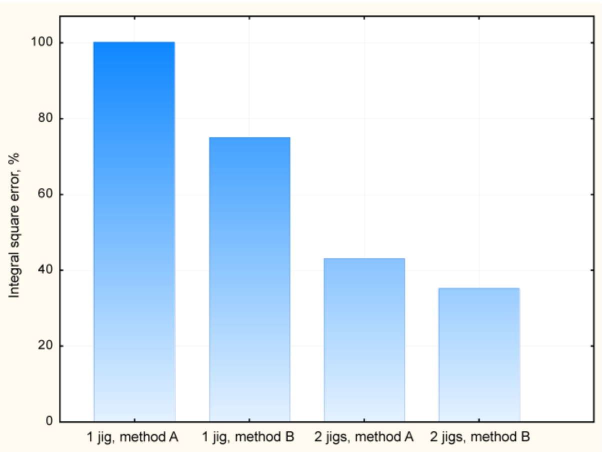

Fig. 5. Values of integral square error for N1 share change of 50%→100%

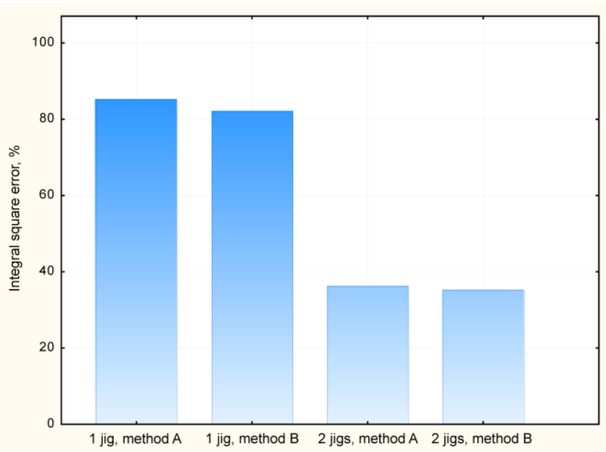

Fig. 6. Values of integral square error for N1 share change of 100%→50%

References

1. Boron S., Heyduk A., Pielot J.: *Application of on-line visual analysis of feed particle size distribution to the multiple coal enrichment systems – evaluation of economic efficiency*. Proceedings of 19th International Conference: Mineral Engineering Conference MEC 2014, Istebna, 15-18 September 2014.
2. Boron S., Pielot J., Wojaczek A.: *Coal cleaning in jig systems – profitability assessment*, Mineral Resources Management, 30(2), 2014, pp. 67-82.
3. Cierpisz S.: *Automatic regulation of coal preparation in jigs* (Automatyczna regulacja procesu wzbogacania węgla w osadzarkach). Silesian University of Technology Press, Gliwice 2012.
4. Cierpisz S.: *Coal production maximization in gravity coal enrichment process control units* (Maksymalizacja produkcji w układach sterowania procesami grawitacyjnego wzbogacania węgla). Proceedings of EMTECH 2016 Coference, Katowice, 2016, pp. 206-212.
5. Cierpisz S., Kaula R.: *Selection of regulator parameters for an inertial object with time delay exemplified on a pulsating jig* (Dobór parametrów regulatora dla obiektu inercyjnego z opóźnieniem na przykładzie osadzarki pulsacyjnej). Mechanizacja i Automatyzacja Górnictwa, 3 (517), 2014, pp. 5-13.
6. Głowiak S.: *Impact of the feed grain composition on the effieciency of preparation in a jig* (Wpływ składu ziarnowego nadawy na skuteczność wzbogacania w osadzarce). Proceedings of the 15th Conference of Minerals Processing Automation, Szczyrk, 2–4 June 2009, pp. 37-50.
7. Goodman F., McCreery J.: *Coal Preparation Computer Model. v.I.* U.S. Environmental Protection Agency, Washington 1980.
8. Heyduk A: *Topographic analysis of two-dimensional images of grains* (Topograficzna analiza dwuwymiarowych obrazów materiału ziarnistego). Mechanizacja i Automatyzacja Górnictwa, 2 (456), 2009, pp. 5-10.
9. Heyduk A.: *Non-segmentic methods of visual assessment of grain composition (*Teksturowe (niesegmentacyjne) metody wizyjnej oceny składu ziarnowego). Mechanizacja i Automatyzacja Górnictwa, 3 (469), 2010, pp. 16–24.
10. Heyduk A., Pielot J.: *Economical Efficiency Assessment of an Application of On-line Feed Particle Size Analysis to the Coal Cleaning System in Jigs*. Inżynieria Mineralna – Journal of the Polish Mineral Engineering Society, 2(34), 2014, pp. 217-228.
11. Kaula R.: *Selection of PI regulator settings in the regulation of coal preparation processes* (Dobór nastaw regulatora PI w układach regulacji procesów wzbogacania węgla), Gospodarka Surowcami Mineralnymi, 31(1), 2015, pp. 141-154.
12. Kaula R., Pielucha W.: *Układ regulacji procesu produkcji mieszanek węgla z regulatorem cyfrowym – studium przypadku*. (Regulation system for coal mixtures production with a digital regulator – case study). 3rd Polish Mining Congress, Wrocław 2015.
13. Pielot J.: *An analysis of effects of coal jigging after changes in the grain composition of a feed*. Archives of Mining Sciences, 55(4), 2010, pp. 827-846.
14. Pielot J.: *Wpływ zmian składu ziarnowego nadawy na efekty wzbogacania węgla w układach osadzarek*. (The impact of changes in the feed grain composition on coal preparation in jigs). Mechanizacja i Automatyzacja Górnictwa, 10 (488), 2011, pp. 32-39.
15. Pielot J.: *Wielokryterialna optymalizacja produkcji układów technologicznych grup wzbogacalników grawitacyjnych* (Multi-criteria method of production optimization in technological systems of gravitational separators groups). Silesian University of Technology Press, Gliwice 2011.
16. Pielot J.: *Wybrane zagadnienia hierarchicznego sterowania i zarządzania w zakładzie przeróbki węgla – cz.I.* (Selected issues of hierarchical control and management in a coal preparation plant – part 1). Mechanizacja i Automatyzacja Górnictwa, 3 (517), 2014, pp. 37-44.
17. PN-88/ M-42000: *Automatyka i pomiary przemysłowe. Terminologia. (Automation and industrial measurements).*
18. Tatjewski P.: *Sterowanie zaawansowane obiektów przemysłowych. Struktury i algorytmy*. (Advanced control of industrial objects. Structures and algorithms). Akademicka Oficyna Wydawnicza EXIT, Warszawa 2002.
19. Trybalski K.: *Analiza właściwości dynamicznych procesów i układów technologicznych przeróbki surowców mineralnych*. (Analysis of dynamic properties of technological processes and systems in minerale processing). Rozprawy Monografie No 83, UW AGH, Kraków 1999.

JOACHIM PIELOT
WOJCIECH PIELUCHA
Silesian University of Technology
joachim.pielot@polsl.pl;