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Evaluation of fine coal upgrading effects by means of Fuerstenau curves

Introduction

The energy safety of Poland is based mainly on the production of electric and heat power on the basis of hard coal which occurs from the fact of possessing a significant amount of deposits of hard coal and lignite. In 2016, balance resources of hard coal deposits identified in detail (in categories A, B, C_1) were equal to 26,410.94 million tons and constituted 45.09% of the total sum of documented balance resources. Hard coal extraction in 2016 was equal to 66,484 thousand tons, and compared to 2015, it increased by 1,414 thousand tons (that is by 2.17%) (http://baza.pgi.gov.pl 2016). It is thus the basic energy carrier and the aware stopping of its extraction would be highly inconvenient, which is underlined in such works as (Fuksa 2016; Gawlik and Mokrzycki 2017; Motowidlak 2018). Having regard to the environmental aspect in the area of the emission of products of coal combustion into the atmosphere, the energy production from coal should cause the necessity to pay close attention to the quality of commercial coal used for the professional power sector. Coal size categories produced at coal processing facilities in technological systems are subjected to a range of processes which are to increase the usable value of ready products through the elimination of the excessive amount of contaminants and harmful substances which can be released and enter the atmosphere in conditions of increased temperature, that is combustion. Mean ash

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contents in deposits of the Upper Silesian Coal Basin range from 4.2% to 62%, total sulfur contents 0.4–3.5%, while from the Lower Silesian Coal Basin: from 10.1% to 38.77% of ash content and 0.69–1.61% of total sulfur content. Steam coals occur mainly in the Lublin Coal Basin, including gas-coking coal types 31–34. The ash content in deposits of the Lublin Coal Basin is on average equal to 6.15–18.11%, and the mean contents of the total sulfur in separate deposits are equal to 1.35% to 3.12% (http://baza.pgi.gov.pl 2016). Due to the considerable diversification in the amounts of contaminants of the mined beds of separate deposits, firstly, the removal of non-useful substances as far as this is possible and effective, using methods and processes of mechanical processing, is required before operations leading to energy production from hard coal are performed (Blaschke 2008). Excavated coal material in all coal processing facilities functioning in Poland is subjected to processing which in upgrading cycles takes account of gangue and high-ash middlings removal in heavy fluid separators, in jigs, water cyclones, coil separators and by means of flotation. Depending on the quality of raw coal, the less or more accurate upgrading of the excavated material is performed. The processing technological system, selection of separate upgrading methods and even devices are conditioned by properties of coals used for processing. The decisive criterion for fuel practical values is the creation of a possibility of the most ideal purification of raw coal, which is the complete separation of gangue from the extracted material and removal of the greatest number of free grains of pyritic sulfur. Classic methods of gravity upgrading are the cheapest way to improve the quality of produced size categories. The degree of purification of upgraded coal from ash and sulfur by these methods is varied. It depends on the way mineral admixtures are connected to the organic phase of coal and on the percentage share of organic sulfur and pyritic sulfur. Additionally, the way in which pyritic sulfur is connected to the grains of the extracted material, that is whether it creates concretions with coal, with gangue or whether there are released pyrite grains, is important (Blaschke 2009). Coal upgrading technologies aiming at improving the quality of the final products are commonly known, but have not always been used for various reasons. It must be noted that the majority of processing facilities has been functioning in the current form since raw un-upgraded fine coal with high contents of ash and sulfur started to be used in the power sector. This situation changed due to gradually introduced modernizations to coal processing facilities consisting in introducing fine coal upgrading in fine coal jigs, and later coal muds through flotation or upgrading in coil separators.

Coal upgrading in water jigs currently constitutes the main source of fine coal production for the needs of the professional power sector. Upgraded coal constitutes 80% of the general production at facilities producing steam coals, while for coking coal processing plants the production is based mainly on multicomponent mixtures of fine coal being produced on the basis of concentrates being upgraded in fine coal jigs.

Quality parameters of the produced commercial size categories measured mainly by ash and sulfur content and calorific value depend on the operational accuracy of these separating devices. In turn, different types of factors, related to the construction, movement (technological) or the feed properties, affect the jig operational results.

In this paper, the effect of the jig's hydrodynamic factors that is a change in the amount of the fed additional hutch water on the separation results was examined. The additional hutch water fed to the jig conditions the appropriate degree of loosening in the jig's operational space, allowing grains for the most free movement during lifting and falling cycles necessary for the concentration of grains with strictly specified density in their equilibrium layer, that is in separation products (Cierpisz and Joostberens 2015; Heyduk and Pielot 2014; Surowiak 2014, 2018; Surowiak and Brożek 2016).

For the purposes of the presentation of raw material upgrading results, calculations based on the quantitative-qualitative analysis of the feed separation into products are made. The simplest method of graphic presentation of upgrading results is based on the analysis of the content of a given component in the feed, concentrate and tailings according to the obtained densimetric fractions in the case of hard coals. Function $\gamma = f(\lambda)$ presents the dependence between the yield and content of a given component in upgrading products and the basic upgrading curve is its graphical representation. This information is often not sufficient due to the fact that increasing emphasis is placed on the separation accuracy expressed by the maximum cumulation of the useful component in the concentrate and possibly large cumulation of non-useful matter in tailings. In this connection, there is a need to illustrate separation results in a different way than the one which has been preferred or considered generally applicable until now (Szymkowiak and Drzymała 2010). A tool enabling to evaluate the effectiveness of upgrading one product with the useful component and simultaneously another product with the non-useful component is the methodology provided by Fuerstenau. Fuerstenau curves constitute a good tool to evaluate the selectivity of separation of two components occurring in a material in order to determine the dependence of recoveries of one component in the concentrate in the function of the second analyzed component in tailings (Drzymała and Ahmed 2005; Drzymała 2007). For the analysis of the effectiveness of a given process leading to the production of a product while taking account of the evaluation of the selectivity of separation of components occurring in the raw material, these curves are applicable in the evaluation of concentrate quality in terms of combustible and volatile matter and ash or sulfur in tailings. A Fuerstenau curve enables the optimum quality of concentrate based on the point of greatest convexity $f_{F,}$ the intersection point with an ideal upgrading curve F to be determined or the possible application of other assumed constant evaluating criterion (Foszcz 2013; Foszcz et al. 2015). The simplest way to evaluate the separation selectivity is to determine point F. This point is obtained by drawing diagonal F on a Fuerstenau diagram with coordinates (0,0) and (100,100). there is the optimum upgrading point corresponding to the equity of the recovery of combustible matter in the concentrate and recovery of residues in tailings $\varepsilon = \varepsilon_r$ at the intersection point of the diagonal with the Fuerstenau curve, which in the case of coal, constitutes the recovery of sulfur or ash in tailings.

The paper presents the evaluation of efficiency of the process of fine coal jigging depending on the amount of additional water being delivered to the device. The efficiency was evaluated by means of Fuerstenau upgrading curves because of the fact that they make the evaluation of differences of separation process efficiency easier. Furthermore, they allow to determine optimal point due to combustible matter recovery in the concentrate by a certain level of gangue or sulfur recovery in tailings.

1. Materials and methods

The results coming from the industrial testing were applied to determine the characteristics of fine coals' upgrading in a jig depending on the amount of the fed additional hutch water. For this purpose, representative samples of products of separation were taken from a jig operating with three products at one of the mechanical coal processing facilities. The machine performance was maintained at the constant level and was equal to 300 Mg/h, while a variable parameter was the amount of additional water equal to respectively 35, 50 and 70 m^3/h. Each taken separation product was subjected to the float and sink analysis in zinc chloride solutions obtaining fractions with densities –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 and +2.0 Mg/m^3. Then, each densimetric fraction was sieved on the appropriate set of sieves which allowed narrow size-density fractions to be obtained. In each size-density fraction, chemical analyses for ash contents and total sulfur contents were performed. The feed for the jig was obtained by balancing yields and contents of ash and sulfur accordingly for a given particle size fraction and density fraction. The mean ash content in the feed was equal to 44.7% and the mean sulfur content was equal to 4.3%.

2. Results and discussion

Data characterizing feeds being directed to beneficiation was obtained as a result of balance calculations (Stępiński 1964) and was presented in Table 1.

Yields of class-fractions obtained from all experiments with separation products in a jig along with chemical analyses are presented in Tables 2–4. Data characteristics of the feed in separate particle size fraction and the feed as a whole of the upgraded material was obtained as a result of balance calculations (Stępiński 1964). The obtained results allowed coordinates and draw Fuerstenau upgrading curves to be calculated for the feed and for separated narrow particle size fraction. These curves were drawn in the system: the recovery of volatile and combustible matter in the concentrate ε – the ash recovery in tailings ε' and the recovery of volatile and combustible matter in the concentrate – the recovery of sulfur in tailings ε''.

Figures 1 and 2 present dependencies of the ash and sulfur recovery in tailings on the recovery of the combustible substance in the concentrate for the feed upgraded in a jig depending on the amount of hutch water. Selectivity indices of upgrading for the feed determined on the basis of the so-called optimum point *F*, at which the recovery of the investigated component in the concentrate is equal to the recovery of the remaining components in tailings, are presented in Table 4. The values of the selected evaluating criterion of upgrading

Table 1. Yields, ash and sulfur grades in feeds from balance

Table 1. Wychody, zawartości popiołu i siarki w nadawach z bilansu

Fraction density [Mg/m^3]	Fraction yield [%]	Ash grade [%]	Sulfur grade [%]	Yield of fraction [%]	Ash grade [%]	Sulfur grade [%]	Yield of fraction [%]	Ash grade [%]	Sulfur grade [%]
	hutch water 35 m^3/h			hutch water 50 m^3/h			hutch water 70 m^3/h		
–1.30	33.03	3.85	0.71	7.30	3.62	1.04	22.61	7.14	0.17
1.3–1.4	12.16	8.21	0.30	5.66	5.47	1.12	8.58	19.30	0.12
1.4–1.5	2.37	14.20	0.13	3.54	8.21	1.51	3.42	25.40	0.06
1.5–1,6	1.80	26.62	0.13	1.77	15.33	2.37	2.25	36.90	0.05
1.6–1.7	1.89	35.12	0.20	2.07	27.08	3.69	2.24	42.50	0.07
1.7–1.8	2.31	41.10	0.54	3.69	29.81	4.28	1.95	51.63	0.26
1.8–2.0	8.14	52.60	0.82	15.96	43.58	5.90	6.03	54.20	2.17
+2.00	38.30	65.80	2.12	60.01	67.47	12.84	52.90	74.50	4.93

at point F, which presumes the equity of the useful component recovery in the concentrate and non-useful component in tailings, indicate the more effective separation of combustible substances from ash in comparison to the separation of the combustible substance from sulfur. Another evaluating criterion of upgrading effectiveness is assuming the maximum of the Fuerstenau curve curvature, that is characteristic point f_F denoting the maximum of change dynamics of the organic substance recovery in the concentrate in relation to the change in ash or sulfur recovery in tailings (Foszcz 2013). The determined values of indices f_F assume lower values in comparison to values of index F for the recovery of the combustible substance in the concentrate in comparison to the recovery of non-useful components in tailings. This indicates that the recovery of the mineral phase in tailings is better, but as a consequence lowering the level of the organic phase substance in concentrate also occurs. It is worth considering to develop and assume another evaluating criterion which would allow to maximize the recovery of non-useful substances in tailings, however, the risk of lowering the level of the useful component in the concentrate most certainly would appear (Foszcz et al. 2015).

The qualitative analysis of separation products obtained as a result of balance calculations depending on the changeable amount of the delivered bottom water to a jig was positioned in Table 5. From the presented data it can be concluded that both quantitative and qualitative separation of coal fines feed in a jig is related to the hydrodynamic conditions of device work and depending on the requirements of the potential recipient, the nature of the device work can be adjusted for the purpose of achieving optimal qualitative parameters of the final products.

Table 2. Yields, ash and sulfur contents in particle size fraction, system efficiency 300 Mg/h, amount of hutch water 35 m^3/h

Tabela 2. Wychody, zawartości popiołu i siarki w klasach ziarnowych, wydajność systemu 300 Mg/h, ilość wody podsitowej 35 m^3/h

Fraction density [Mg/m^3]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]
	fraction < 2.0 mm			fraction 2.0–3.15 mm			fraction 3.15–5.0 mm			fraction 5.0–6.3 mm			fraction 6.3–8.0 mm		
–1.3	28.97	5.56	1.08	29.78	1.53	0.91	28.84	7.17	2.71	27.85	4.03	1.05	25.96	7.12	1.19
1.3–1.4	12.33	8.74	2.91	19.87	6.70	1.37	20.21	6.31	1.42	15.19	6.14	1.45	9.04	6.33	1.59
1.4–1.5	4.00	13.86	2.59	3.90	13.21	2.29	3.15	13.69	2.51	2.67	13.29	3.18	2.03	12.53	3.64
1.5–1.6	3.31	26.36	4.60	2.42	23.34	3.67	2.10	24.01	4.03	1.56	25.10	4.98	1.69	28.40	5.80
1.6–1.7	2.62	25.29	5.10	2.33	32.76	5.62	2.21	33.98	6.35	2.01	34.50	5.93	1.87	37.46	7.22
1.7–1.8	2.60	33.03	6.76	2.12	39.30	6.99	2.61	40.69	6.97	3.14	40.11	6.03	2.89	41.44	7.00
1.8–2.0	11.25	43.03	7.73	9.59	45.77	7.73	8.90	46.10	9.17	9.96	48.20	9.56	10.74	49.70	7.92
+2.0	34.91	56.60	12.89	29.99	62.50	16.66	32.00	64.50	14.01	37.61	63.40	14.86	45.79	63.10	13.62
Calculated feed	100.0	30.24	6.61	100.0	27.6	6.74	100.0	30.83	6.85	100.0	33.4	7.52	100.0	39.28	8.05

Fraction density [Mg/m^3]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]
	fraction 8.0–10.0 mm			fraction 10.0–12.5 mm			fraction 12.5–16.0 mm			fraction 16.0–20 mm			fraction 20.0–25.0 mm		
–1.3	27.17	2.63	1.00	32.48	2.83	0.67	40.83	3.30	0.87	39.53	4.07	1.09	52.75	3.57	0.78
1.3–1.4	7.07	7.46	1.95	4.39	9.05	2.39	4.72	7.13	2.82	9.36	9.33	3.19	6.56	11.63	3.65
1.4–1.5	1.44	15.80	2.85	1.51	16.68	5.67	2.34	16.93	6.06	3.89	16.34	5.79	2.60	16.27	7.60
1.5–1.6	1.20	31.40	4.98	1.08	33.50	7.30	1.59	26.40	8.14	2.85	26.30	7.51	1.35	33.90	2.61
1.6–1.7	1.55	39.20	5.62	0.80	39.40	9.50	1.18	38.50	10.60	2.42	40.10	9.30	1.44	31.50	12.29
1.7–1.8	1.97	40.02	6.06	1.24	45.30	11.40	1.14	41.60	12.70	2.45	49.00	10.00	2.42	41.00	16.30
1.8–2.0	6.96	52.70	8.71	4.99	46.88	12.30	5.04	43.72	13.68	6.51	57.00	18.33	4.75	53.39	6.06
+2.0	52.64	63.10	14.00	53.52	72.10	11.50	43.17	68.10	10.74	32.98	73.90	7.28	28.12	80.20	0.98
Calculated feed	100.0	40.12	8.69	100.0	43.75	7.47	100.0	35.03	6.35	100.0	34.13	5.23	100.0	30.06	2.02

Table 3. Yields, ash and sulfur contents in particle size fraction, system efficiency 300 Mg/h, amount of hutch water 50 m^3/h

Tabela 3. Wychody, zawartości popiołu i siarki w klasach ziarnowych, wydajność systemu 300 Mg/h, ilość wody podsitowej 50 m^3/h

Fraction density [Mg/m^3]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]
	fraction < 2.0 mm			fraction 2.0–3.15 mm			fraction 3.15–5.0 mm			fraction 5.0–6.3 mm			fraction 6.3–8.0 mm		
–1.3	17.49	4.65	1.13	22.67	3.50	0.94	22.84	3.46	0.89	20.95	2.96	0.81	19.91	2.91	0.74
1.3–1.4	9.20	7.30	1.14	10.78	5.96	1.14	8.60	5.93	1.12	7.88	6.24	1.14	4.91	5.90	1.11
1.4–1.5	5.47	10.31	1.83	6.00	8.32	1.34	4.51	10.27	2.07	2.66	7.70	1.57	2.45	9.05	1.66
1.5–1.6	3.44	15.60	2.94	2.92	14.90	2.04	1.98	18.00	2.71	1.44	18.00	2.40	1.13	24.00	2.20
1.6–1.7	4.10	28.10	4.84	3.37	28.40	3.93	3.07	30.00	4.17	2.55	28.00	3.80	1.81	39.00	5.30
1.7–1.8	4.33	32.40	5.87	3.95	30.40	4.68	4.14	32.70	4.50	3.87	36.00	5.50	3.54	43.00	7.50
1.8–2.0	11.65	48.00	7.77	11.55	46.53	7.71	11.34	47.00	8.02	9.68	43.85	9.47	12.93	47.60	8.53
+2.0	44.31	64.15	17.95	38.76	63.24	22.88	43.53	65.05	21.00	50.97	65.10	17.57	53.32	76.04	9.85
Calculated feed	100.0	39.16	9.82	100.0	34.41	10.55	100.0	38.04	10.81	100.0	41.11	10.52	100.0	50.29	6.98

Fraction density [Mg/m^3]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]
	fraction 8.0–10.0 mm			fraction 10.0–12.5 mm			fraction 12.5–16.0 mm			fraction 16.0–20 mm			fraction 20.0–25.0 mm		
–1.3	15.35	2.86	0.68	14.80	2.62	0.52	14.88	3.39	0.89	17.18	3.00	0.91	22.99	2.22	0.80
1.3–1.4	3.85	7.29	1.60	2.76	8.50	1.40	2.90	6.90	1.03	2.87	9.00	0.62	4.49	8.60	1.23
1.4–1.5	1.00	11.00	2.50	0.65	15.00	3.50	0.37	18.88	3.18	0.49	20.35	1.84	0.67	17.20	8.13
1.5–1.6	0.66	26.00	3.60	0.13	31.00	5.60	0.21	21.00	5.60	0.40	32.70	4.09	0.33	23.80	14.01
1.6–1.7	1.06	35.00	5.90	0.23	39.00	6.90	0.08	35.00	7.90	0.26	45.00	6.80	0.22	42.00	18.40
1.7–1.8	2.24	42.00	7.40	1.04	48.00	9.40	0.72	47.00	12.40	2.10	58.00	9.40	2.98	58.00	10.40
1.8–2.0	11.69	53.00	9.80	11.12	73.00	11.80	11.48	63.00	11.80	13.76	63.00	10.10	21.11	76.00	3.20
+2.0	64.15	72.35	12.29	69.27	90.35	0.69	69.36	85.20	4.33	62.94	77.00	5.33	47.20	90.35	0.69
Calculated feed	100.0	54.92	9.47	100.0	69.27	1.33	100.0	67.51	4.64	100.0	59.47	5.16	100.0	61.60	1.69

Table 4. Yields, ash and sulfur contents in particle size fraction, system efficiency 300 Mg/h, amount of hutch water 70 m^3/h

Tabela 4. Wychody, zawartości popiołu i siarki w klasach ziarnowych, wydajność systemu 300 Mg/h, ilość wody podsitowej 70 m^3/h

Fraction density [Mg/m^3]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]
	fraction < 2.0 mm			fraction 2.0–3.15 mm			fraction 3.15–5.0 mm			fraction 5.0–6.3 mm			fraction 6.3–8.0 mm		
–1.3	15.39	5.87	1.10	15.75	4.03	0.89	17.87	3.34	0.83	20.29	3.39	0.81	21.43	3.69	1.16
1.3–1.4	10.82	7.83	1.36	14.22	6.40	1.33	8.00	3.70	1.17	7.83	6.24	1.33	6.92	7.51	1.31
1.4–1.5	6.80	9.14	1.50	6.61	8.11	1.40	4.95	8.71	1.54	3.62	8.61	1.67	2.36	9.07	1.82
1.5–1.6	4.81	11.70	1.67	4.80	10.61	1.69	3.55	11.18	1.80	2.77	11.74	2.35	1.39	14.34	2.14
1.6–1.7	3.83	15.70	2.30	4.18	14.05	2.20	3.75	14.90	2.52	3.06	13.40	2.40	2.10	17.00	2.61
1.7–1.8	2.87	21.10	3.24	3.10	20.70	2.97	3.15	21.05	3.71	2.68	25.70	3.84	2.02	87.90	4.86
1.8–2.0	9.09	48.60	7.69	7.80	42.70	8.05	6.98	40.72	7.73	8.88	41.10	8.73	6.66	45.80	8.64
+2.0	46.38	70.15	18.52	43.54	69.94	23.64	51.75	46.00	23.13	50.86	66.92	18.84	57.11	72.45	16.31
Calculated feed	100.0	41.10	9.97	100.0	37.60	11.61	100.0	29.59	13.10	100.0	40.60	10.93	100.0	47.27	10.46

Fraction density [Mg/m^3]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]	Fraction yield [%]	Ash content [%]	Sulfur content [%]
	fraction 8.0–10.0 mm			fraction 10.0–12.5 mm			fraction 12.5–16.0 mm			fraction 16.0–20 mm			fraction 20.0–25.0 mm		
–1.3	22.99	3.04	0.66	25.34	3.08	0.75	29.47	3.19	0.89	25.30	2.73	0.87	38.13	4.12	0.64
1.3–1.4	5.99	9.38	1.24	6.01	7.55	1.61	6.14	10.14	1.65	7.65	8.26	2.30	9.39	8.46	0.79
1.4–1.5	1.50	18.50	1.96	1.07	17.48	3.87	0.94	21.55	3.27	1.47	22.28	3.38	1.51	19.38	2.53
1.5–1.6	1.00	25.80	2.56	0.46	22.30	4.52	0.21	29.00	4.30	0.74	36.40	3.80	0.25	26.40	3.40
1.6–1.7	1.69	32.00	3.42	0.65	35.20	5.12	0.45	35.40	5.40	0.16	45.70	5.30	0.14	38.20	4.10
1.7–1.8	1.31	36.20	4.75	0.50	51.30	6.80	0.66	51.30	7.30	0.91	56.70	4.60	0.63	47.60	4.90
1.8–2.0	5.05	47.55	5.00	2.44	62.00	7.30	2.88	72.00	9.50	4.19	72.00	1.80	4.42	63.00	5.20
+2.0	60.48	77.90	10.10	63.52	79.44	7.52	59.25	81.70	10.12	59.58	91.60	0.90	45.54	83.92	5.51
Calculated feed	100.0	52.32	6.76	100.0	53.98	5.37	100.0	52.80	6.75	100.0	60.10	1.14	100.0	44.08	3.14

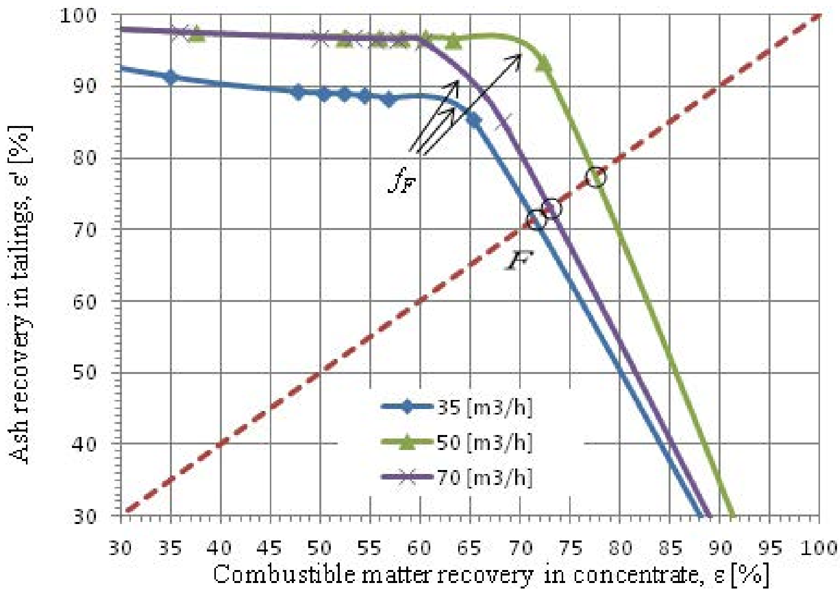

Fig. 1. Fuerstenau upgrading curves for the feed in relation to the ash recovery in tailings

Rys. 1. Krzywe wzbogacania Fuerstenaua dla nadawy względem uzysku popiołu w odpadzie

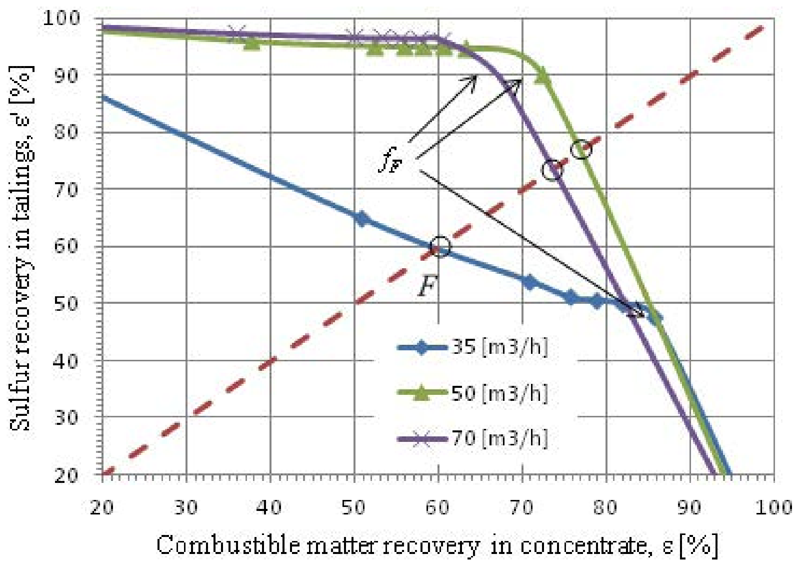

Fig. 2. Fuerstenau upgrading curves for the feed in relation to the sulfur recovery in tailings

Rys. 2. Krzywe wzbogacania Fuerstenaua dla nadawy względem uzysku siarki w odpadzie

Table 5. Juxtaposition of beneficiation products quality depending on conditions of jig work

Table 5. Zestawienie jakości produktów wzbogacania w zależności od warunków pracy osadzarki

Product	Fraction yield [%]	Ash grade [%]	Sulfur grade [%]	Fraction yield [%]	Ash grade [%]	Sulfur grade [%]	Fraction yield [%]	Ash grade [%]	Sulfur grade [%]
	hutch water 35 m^3/h			hutch water 50 m^3/h			hutch water 70 m^3/h		
Concentrate	30.33	7.80	0.54	40.96	7.18	0.53	25.61	5.54	1.04
Middlings	31.01	8.98	2.65	33.92	41.99	8.71	24.86	53.65	8.85
Tailings	38.66	60.11	6.39	25.12	55.88	9.09	49.53	58.57	10.82

Depending on the selected evaluating criterion, points of upgrading selectivity read from the curves in Figures 1 and 2 assume different values. It can be observed in both figures that points f_F and F are significantly different for separate curves, which is also illustrated in Table 6. This means that depending on the selected criterion, it is possible to determine two significantly different points of optimum upgrading. The selection of one of these criteria can be justified additionally by the nature of the conducted process and its possible main technological purpose (the recovery of which product is more important from the process operator's point of view).

The problem of fitting the course of Fuerstenau curve to the industrial results by ores beneficiation was a topic of many research works, conducted by Drzymala et al. (2010), Foszcz and al. (2010), Drzymala et al. (2012). The characteristics of the industrial results of beneficiation has a very specific course, the approximation of which, by means of methods being applied for laboratory investigations, requires adequate corrections (Drzymala et al. 2010). The authors of these works also proved the necessity of analysis of material characteristics for a wider range of the analyzed coefficients for evaluating the separation process

Table 6. Technologically optimal values of recovery determined according to different criteria for the feed

Tabela 6. Technologicznie optymalne wartości uzysku wyznaczone według różnych kryteriów dla nadawy

Parameter	Evaluating criterion	Amount of additional water [m^3/h]		
		35	50	70
Recovery of combustible matter in the concentrate – ash recovery in tailings	F	71.5	73.0	77.5
	f_F	63.0	73.0	64.0
Recovery of combustible matter in the concentrate – sulfur recovery in tailings	F	59.6	77.0	73.5
	f_F	85.0	70.0	63.0

efficiency. In the case of industrial investigations, this is more difficult and requires the application of appropriate corrections in determining the functional relations. The elaboration of the methodology of determining the optimal work of the industrial device together with the determination of the optimal beneficiation point for coal fines would be a valuable tool allowing for a wider analysis and evaluation of hard coal beneficiation.

Figure 3 presents the relation between selectivity index *F* determined for feed depending on the changeable hydrodynamic conditions of jig work, from which it can be concluded that the separation of the organic substances and ash being measured by means of combustible matter recovery in the concentrate and ash in tailings occurs better with the growth of the amount of additional water being delivered to the working chamber of a jig. However, the most profitable separation of combustible matter in the concentrate and sulfur in the tailings was observed for 50 m^3/h of the delivered additional water.

Figures 4–6 present Fuerstenau upgrading curves in the function of ash recovery in tailings, and Figures 7–9 present these curves in the function of sulfur recovery in tailings for narrow the particle size fraction of balanced products of separation in a jig. Tables 7 and 8 contain values of selectivity index *F* determined from these curves, determined for variable jig's hydrodynamic operational parameters. Considerations concerning the analysis of upgrading fine coals in separate particle size fraction are based on this index. The presented data indicates that the separation of ash from the organic phase occurs in the most effective way in particle size fraction greater than 12.5 mm; however, for the case with additional water, it achieves the value of index *F* above 80 only for the greatest particle size.

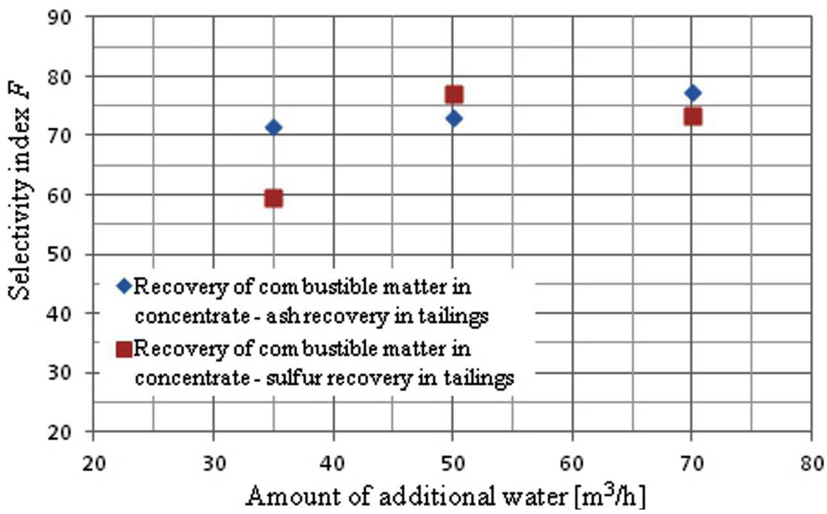

Fig. 3. Values of the separation selectivity index depending on hydrodynamic conditions of jig work

Rys. 3. Wartości wskaźnika selektywności rozdziału w zależności
od warunków hydrodynamicznych pracy osadzarki

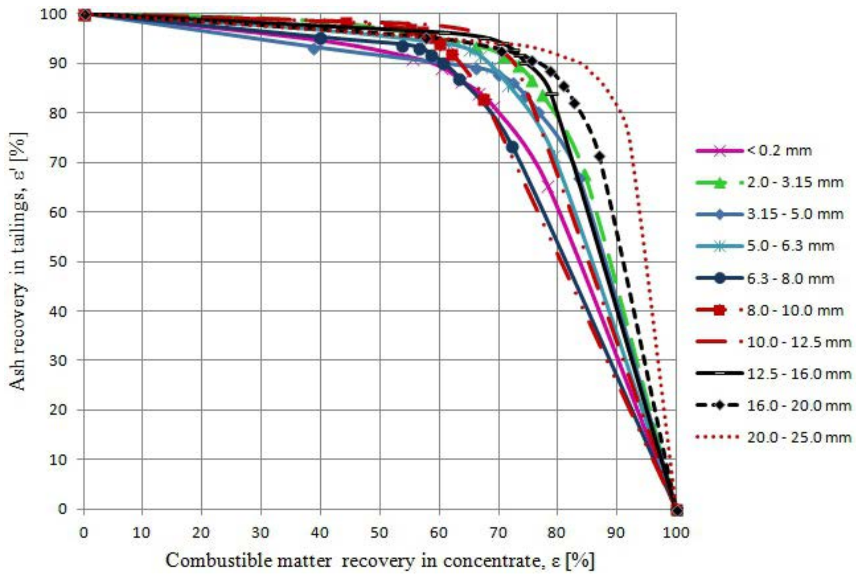

Fig. 4. Fuerstenau upgrading curves inparticle size fraction, amount of hutch water 35 m^3/h

Rys. 4. Krzywe wzbogacania Fuerstenaua w klasach ziarnowych ilość wody podsitowej 35 m^3/h

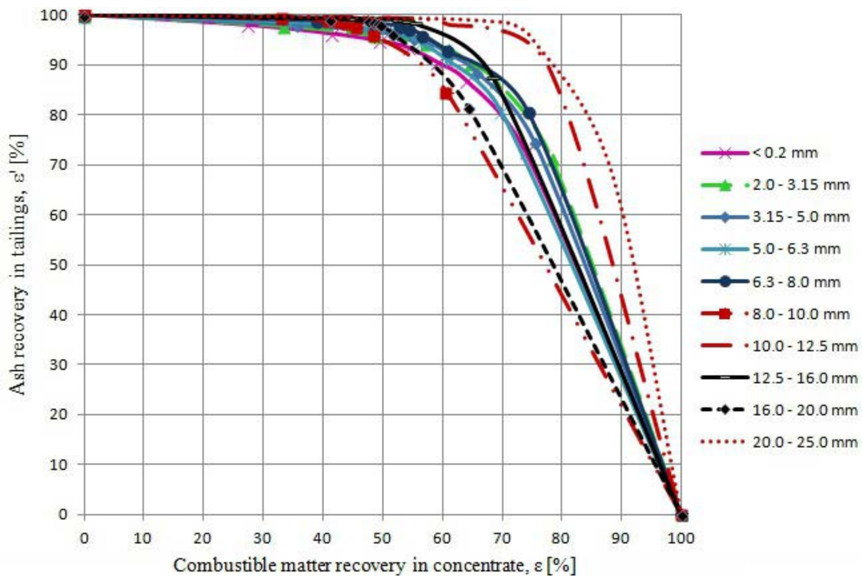

Fig. 5. Fuerstenau upgrading curves in particle size fraction, amount of hutch water 50 m^3/h

Rys. 5. Krzywe wzbogacania Fuerstenaua w klasach ziarnowych, ilość wody podsitowej 50 m^3/h

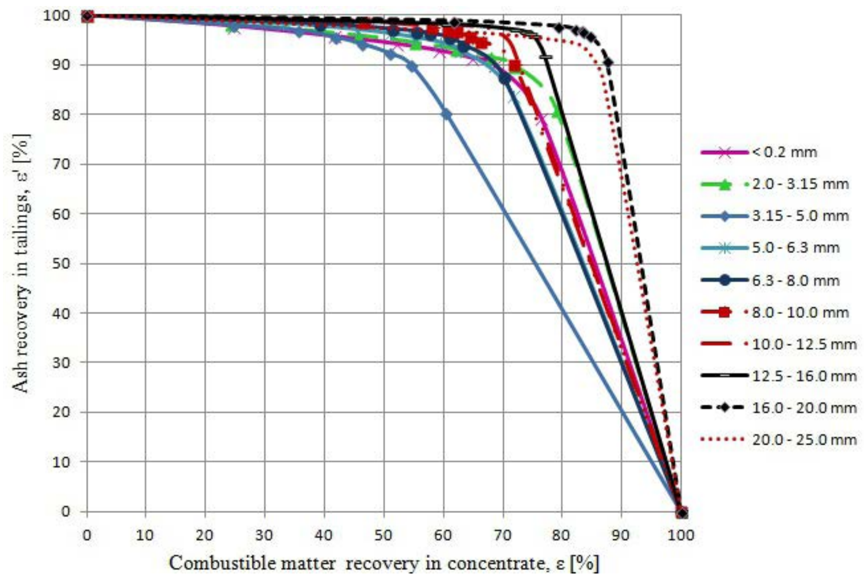

Fig. 6. Fuerstenau upgrading curves in particle size fraction, amount of hutch water 70 m^3/h

Rys. 6. Krzywe wzbogacania Fuerstenaua w klasach ziarnowych, ilość wody podsitowej 70 m^3/h

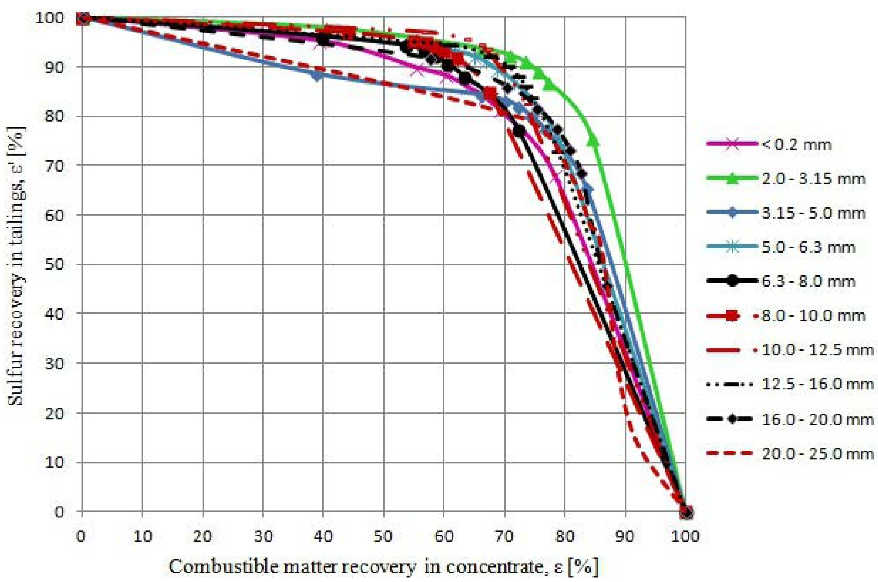

Fig. 7. Fuerstenau upgrading curves in particle size fraction, amount of hutch water 35 m^3/h

Rys. 7. Krzywe wzbogacania Fuerstenaua w klasach ziarnowych, ilość wody podsitowej 35 m^3/h

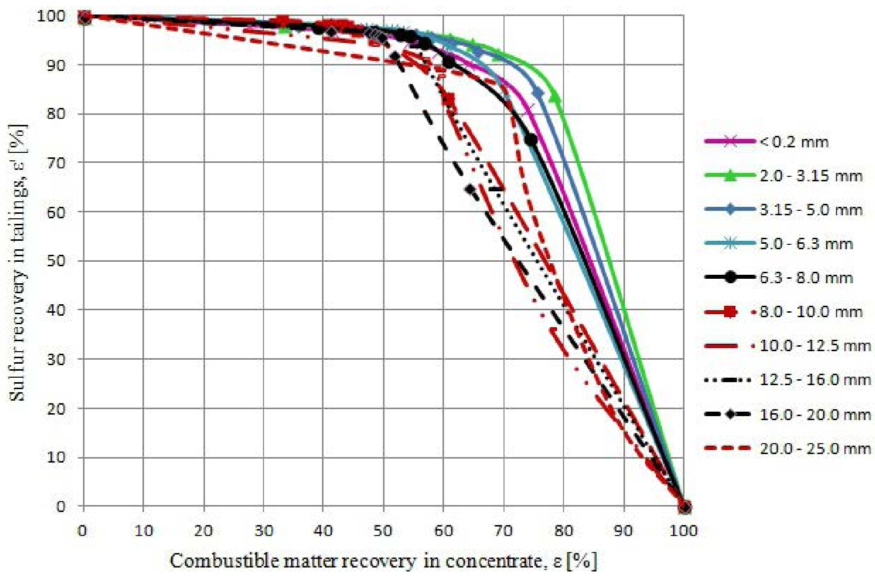

Fig. 8. Fuerstenau upgrading curves in particle size fraction, amount of hutch water 50 m^3/h

Rys. 8. Krzywe wzbogacania Fuerstenaua w klasach ziarnowych, ilość wody podsitowej 50 m^3/h

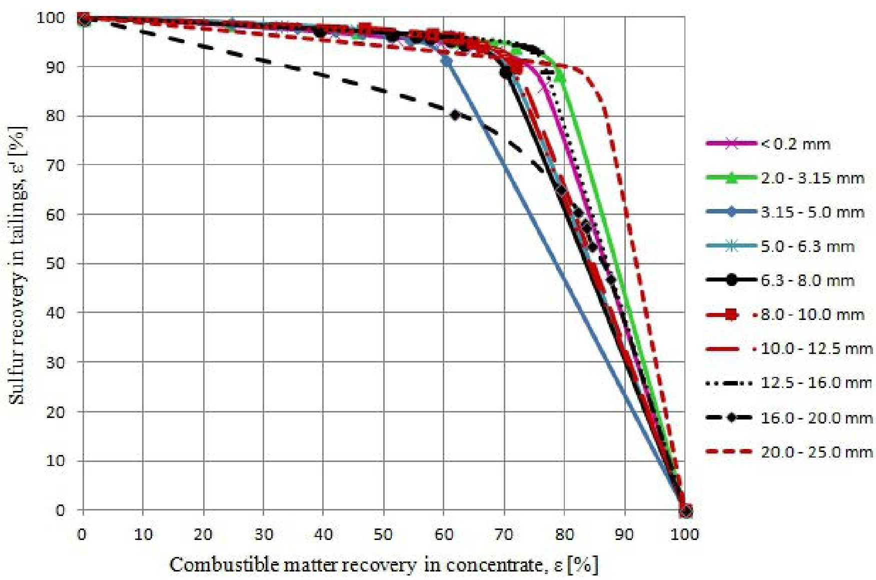

Fig. 9. Fuerstenau upgrading curves in particle size fraction, amount of hutch water 70 m^3/h

Rys. 9. Krzywe wzbogacania Fuerstenaua w klasach ziarnowych, ilość wody podsitowej 70 m^3/h

Table 7. Selectivity index *F* for ash recovery in tailings

Tabela 7. Wskaźnik selektywności *F* dla uzysku popiołu w odpadach

Amount of additional water [m^3/h]	Particle size fraction [mm]									
	< 2.0	2.0–3.15	3.15–5	5.0–6.3	6.3–8.0	8.0–10.0	10.0–12.5	12.5–16.0	16.0–20.0	20.0–25.0
35	74	79.5	78	77	72.5	72.0	77.0	80	82	87
50	74	76	75	73	76.0	67.5	79.0	74	70	83
70	77	79	67	75	74.0	75.5	76.5	80	88	87

Table 8. Selectivity index *F* for sulfur recovery in tailings

Tabela 8. Wskaźnik selektywności *F* dla uzysku siarki w odpadach

Amount of additional water [m^3/h]	Particle size fraction [mm]									
	< 2.0	2.0–3.15	3.15–5	5.0–6.3	6.3–8.0	8.0–10.0	10.0–12.5	12.5–16.0	16.0–20.0	20.0–25.0
35	77	82	77	78	74	72	76	77.5	78	77
50	76	80	78	74	75	68	68	67.0	65	72
70	79	81	70	76	75	76.5	76	79.5	73	85

The lowest values of index F lower than 70 were observed for particles with sizes 8.0––10.0 mm and 3.15–5.0 mm for the amount of hutch water respectively equal to 50 and 70 m^3/h. On the other hand, the selectivity of the separation of sulfur in tailings from the combustible substance in the concentrate was the lowest in fractions with size 8.0–20.0 mm in the case of 35 and 50 m^3/h hutch water, that is basically with the majority of coarse particles. Nearly a half of the size fraction from the large particle size range upgrades poorly which is related to the insufficient release of sulfur in these size fraction or to the presence of the so-called sulfur of an origin other than pyrite, which occurs in hard coals.

Figures 4–9 present Fuerstenau curves for narrow particle size fraction, whereby Figures 4–6 contain the analysis in the function of ash recovery in tailings, and Figures 8–9 in the function of sulfur recovery in tailings. In both cases, it can be observed that along with an increase inparticle size, the obtained Fuerstenau curve becomes more symmetrical in relation to the diagonal joining points with coordinates (0, 0) and (100, 100). Of course, in such a case values of optimum separation points f_F and F are close to each other. However, this cannot be said about the smallest particle size fraction where the Fuerstenau curve inflection point lies in a significant distance from the intersection point with the diagonal. This means that in the case of small particle size fraction, the selection of the optimum separation point also depends on the assumed technological purpose and arbitrary decision of the operator.

Conclusions

One of key elements in conducting the process in order to produce concentrates of fine coals for the needs of the professional power sector is to analyze the separation results as regards the evaluation of recoveries of both combustible substances in the concentrate and non-useful substances in tailings. The article presents the Fuerstenau attitude to the evaluation of upgrading results for variable jig's hydrodynamic operational conditions. The ash content and total sulfur content were analyzed as non-useful substances.

The obtained results of the conducted experiments allow the following final conclusions to be formulated:

1. The analysis of the efficiency of device work depending on the influence of the researched parameter, which is amount of hutch water, indicates the necessity of jig work by higher values being higher than 50 m^3/h, which allows a better separation efficiency to be achieved (Fig. 3). The results of the investigations presented in the paper in respect to the influence of hydrodynamic conditions of jig work indicated that it is important to determine optimal conditions of device work to achieve assumed production tasks because the quantitative and qualitative separation of coal fines beneficiated in a jig is related to the amount of hutch water being directed to the device.
2. The methodology of Fuerstenau upgrading curves is an effective tool to evaluate the upgrading of both metal ores and coal. However, attention should be paid to the selection of

one evaluating criterion because the process evaluation depending on different assumed indexes leads to differences in the evaluation of a given process effectiveness. Particularly in the case of small grains, significant differences in values of optimum separation points F and f_F can be noticed. These differences become significantly smaller along with the increase in particle size. This is of crucial meaning for the analysis of industrial data which is characterized by a specific course.

3. Analyzing the separation selectivity in all of the material, lower values of indices F are usually obtained in comparison to the values obtained in narrow particle size fraction.
4. The application of beneficiation curves allows the optimum level of recoveries of combustible substances in the concentrate and non-useful substances in tailings to be determined. The proposed way of obtaining beneficiation curves allows the process to be analyzed in the context of its optimization.
5. The conducted analyses allow to state that the separation of combustible substances from ash occurs much more effectively than the separation of combustible substances from sulfur in coal (Figs 1 and 2).
6. The test results presented in the article as regards the effect of the jig's hydrodynamic operational conditions show that determining the optimum device's operational conditions is important for achieving the expected production tasks.

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EVALUATION OF FINE COAL UPGRADING EFFECTS BY MEANS OF FUERSTENAU CURVES

Keywords

jig, particle size, upgrading, ash and sulfur content, clean coal

Abstract

In recent years, more and more attention has been paid to the quality of produced coal size categories for energy purposes. This is important from the perspective of promoting clean coal technologies which aim at changing the perception of coal as a fuel friendly for the environment. This is specifically because hard coal resources in Poland allow the national energy security to be guaranteed on the basis of energy production based on hard coal. Fine coals upgraded at coal processing facilities in the separation process in fine coal jigs are mainly used in energy production from coal.

In the article, an analysis of hard coal upgrading in a jig regarding the optimum recovery of a useful fraction in the concentrate (combustible and volatile matter) and non-useful fraction in tailings (ash and sulfur) was conducted. Based on the industrial testing of a fine coal jig, the granulometric and densimetric analysis of the taken samples of concentrate, middlings and tailings of coal was conducted in laboratory conditions. Yields of products were calculated in separated size-fractions of separation products, and ash content and total sulfur content were determined in them. Based on the results of granulometric, densimetric and chemical analyses of the obtained size-fractions, the balance of separation products and appropriate calculations, Fuerstenau upgrading curves which allowed the process to be evaluated and a comparison of the results of hard coal upgrading regarding the optimum recovery of the organic phase in the concentrate and mineral components in tailings to be drawn. The obtained results were evaluated on the basis of different criteria for changing the device's hydrodynamic operational conditions. The ash content and total sulfur content were analyzed as non-useful substances.

OCENA EFEKTÓW WZBOGACANIA MIAŁÓW WĘGLOWYCH ZA POMOCĄ KRZYWYCH FUERSTENAUA

Słowa kluczowe

osadzarka, wielkość ziaren, wzbogacanie, zawartość popiołu i siarki, czysty węgiel

Streszczenie

W ostatnich latach coraz większą uwagę zwraca się na jakość produkowanych sortymentów węglowych kierowanych do celów energetycznych. Jest to istotne z punktu widzenia popularyzowania czystych technologii węglowych, które mają na celu spowodowanie postrzegania węgla jako paliwa przyjaznego dla środowiska. Szczególnie, że zasoby węgla kamiennego w Polsce pozwalają na zagwarantowanie bezpieczeństwa energetycznego kraju w oparciu o produkcję energii na bazie węgla

kamiennego. Do produkcji energii z węgla wykorzystuje się głównie miały węglowe wzbogacanie w zakładach przeróbki węgla w procesie separacji w osadzarkach miałowych.

W artykule przeprowadzono analizę wzbogacania węgla kamiennego w osadzarce pod kątem optymalnego uzysku frakcji użytecznej w koncentracie (części palnych i lotnych) i frakcji nieużytecznej w odpadzie (popiołu i siarki). Na podstawie opróbowania przemysłowego osadzarki miałowej wykonano analizę granulometryczną i densymetryczną pobranych próbek koncentratu, przerostu i odpadów węgla w warunkach laboratoryjnych. W wydzielonych klaso-frakcjach produktów rozdziału wyliczono wychody produktów oraz oznaczono w nich zawartość popiołu i siarki całkowitej. Na podstawie wyników analiz granulometrycznych, densymetrycznych i chemicznych uzyskanych klaso-frakcji, bilansu produktów rozdziału oraz stosownych obliczeń wykreślono krzywe wzbogacania Fuerstenau, które pozwoliły na ocenę procesu i porównanie wyników wzbogacania węgla kamiennego pod kątem optymalnego uzysku fazy organicznej w koncentracie i składników mineralnych w odpadach. Dokonano oceny uzyskanych efektów w oparciu o różne kryteria dla zmiennych warunków hydrodynamicznych pracy urządzenia. Jako substancje nieużyteczne analizowano zawartość popiołu i siarki całkowitej.