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ASSESSMENT OF COAL SLURRY DEPOSITS ENERGETIC POTENTIAL AND POSSIBLE UTILIZATION PATHS

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Abstract: Coal-slurries and post-flotation mud have the highest carbon content among other mine waste produced during coal mining and preparation. Therefore, coal slurries deposited in impoundments can be regarded as potential fuel. In the article methods of energetic potential assessments of raw and beneficiated coal slurry deposits were discussed. Results of such assessment for 21 impoundments were presented and the loss of energetic potential due to the imperfection of beneficiation method was discussed. The lowest losses were observed for beneficiation by froth flotation where the loss of energetic potential was on average 15%. The highest loss was observed for beneficiation in centrifugal separators where on average it was 68%. Possible paths of utilization of such slurries in Polish national fuel balance were studied using the SWOT analysis. The results of the SWOT analysis indicate that the internal factors, i.e. the ones related to the coal slurry processing technology have much lower impact on the possibility of using coal slurry deposits in the national fuel balance. Instead, according to the experts, external factors have much greater impact.

Keywords: *coal slurry, tailings, beneficiation, SWOT analysis, fuel*

Introduction

Fine grained tailings such as coal-slurries and post-flotation mud have the highest carbon content among other mine wastes produced during coal mining and preparation (Niedoba 2013, Lutynski and Szpyrka 2011, Blaschke 2005). Therefore, it is crucial to find an effective method to utilize their energetic potential, which is contained in the coal slurry deposits. Usually, coal-slurry beneficiation or direct utilization by combustion in fluidized-bed boilers is considered.

Current beneficiation methods allow obtaining fine-grained high quality coal products (Lutynski and Blaschke 2009, Lutynski 2009, Taoa 2002). Nevertheless, tailing still contains some carbonaceous matter, which is inevitable despite the application of modern beneficiation methods. We performed investigations focused on

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the possibility of coal slurry beneficiation by several methods. The results were described elsewhere (Szpyrka and Lutynski 2012). The applied methods included:

- centrifugal separation with the use of hydrocyclone classifier-separator and centrifugal separator,
- wet gravity separation with the use of Reichert spiral separator LD4,
- physicochemical method – flotation.

Application of each method resulted in the increase of calorific value of the concentrate in comparison to the raw coal-slurry deposited in impoundment where it was sampled. However, every single method resulted in the loss of energetic potential due to the fact that the coal matter was not completely separated from the tailing.

Determination of coal slurry deposits energetic potential

The basic quality (Lutynski et al. 2013) and quantity (Witkowska-Kita et al. 2012) analysis of coal slurries were performed allowing initial assessment of energetic potential of these deposits. In order to determine the energetic potential of the coal slurries an assessment algorithm was developed. Two options of energetic potential assessment were proposed. The first one gives a rough estimate of energetic potential of coal slurry deposit (impoundment) and is calculated taking into account the following factors:

- estimated mass of coal slurry in the impoundment,
- average calorific value determined, based on the qualitative investigation of samples collected from the impoundment.

These data serve as the approximate estimation of energetic potential which is commonly reported in qualitative studies. It is important information but for a more detailed knowledge regarding the coal slurry deposit it is necessary to give a range of energetic potential uncertainty. Therefore, in addition to the mean energetic potential, the upper and lower limits are given based on the standard deviations of calorific values in each test. It is known from the probability theory that 68% of the values (for normal distribution) are within the standard deviation from the mean, i.e. values of individual samples. The normal distribution pattern was observed for calorific values at individual impoundment. Therefore such an assumption was made (Grudzinski 2005). Thus, average energetic potential of individual coal slurry deposit (impoundment) for as received or in analytical state can be calculated using the following formula:

$$E_{avg} = M\, Q^{a}_{avg} \cdot 10^{-3} \tag{1}$$

where E_{avg} denotes mean energetic potential of the coal slurry deposit (impoundment) in GJ, M estimated mass of coal slurry in the deposit in Mg, Q^{a}_{avg} mean calorific value in the analytical state in kJ/kg determined by qualitative tests of individual samples collected from the impoundment. The Q^{a}_{avg} value can be estimated using the formula:

$$Q^a_{avg} = \frac{1}{n}\sum_{i=1}^{n} Q^a_i \, . \tag{2}$$

Formulas for calculation of the maximum (E_{max}) and minimum (E_{min}) coal slurry deposit energetic potential, in GJ, are:

$$E_{max} = M\,(Q^a_{avg} + S_Q) \cdot 10^{-3} \tag{3}$$

and

$$E_{min} = M\,(Q^a_{avg} - S_Q) \cdot 10^{-3} \tag{4}$$

where S_Q is a standard deviation of calorific value calculated using the following formula:

$$S_Q = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(Q^a_i - Q^a_{avg}\right)} \, . \tag{5}$$

Results of calculations for the 21 impoundments are presented in Table 1.

Table 1. Energetic potential of coal slurry deposits at analytical state

Impoundment	Estimated mass	Average calorific value	Calorific value standard deviation	Energetic potential at analytical state		
				Average	Maximum	Minimum
	Mg	kJ/kg	kJ/kg	GJ	GJ	GJ
K13	1 000 000	15 096	1509	15095667	16604265	13587068
K14	300 000	15 646	830	4693800	4942657	4444943
K12	1 000 000	14 813	581	14812667	15393327	14232006
K18/1	100 000	9 325	2052	932547	1137768	727326
K18/2	100 000	10 073	2747	1007325	1281976	732674
K11/1	640 000	13297	2413	8509964	10054237	6965690
K3/1	1 521 000	9265	3498	14092825	19413371	8772280
K3/2	176 000	14877	5976	2618308	3670019	1566597
K2	1 117 000	12304	2803	13743987	16874910	10613064
K17	155 000	22807	1538	3535074	3773403	3296745
K1	153 000	23293	1444	3563810	3784749	3342871
K4/1	345 600	22941	590	7928525	8132297	7224753
K4/2	163 000	15813	937	2577600	2730378	2424822
K4/3	460 000	20829	2065	9581173	10530941	8631404
K5/1	130 000	12051	1504	1566590	1762060	1371119
K5/2	228 000	17802	5351	4058928	5279050	2838807
K5/3	106 000	19402	646	2056612	2125131	1988132
K5/4	102 000	20351	844	2075761	2161898	1989625
K11/2	176 000	19672	767	3462345	3597362	3327329
K6	236 000	18887	1834	4457435	4890353	4024518

The other option of coal slurry deposit energetic potential assessment is more detailed and requires data such as the type of coal slurry and method of its beneficiation. The energetic potential is calculated taking into account the following:

- mass of coal slurry in the impoundment,
- concentrate yield of beneficiation method,
- average calorific value of concentrate from technological tests.

In order to compare different beneficiation methods it was decided to estimate the energetic potential at analytical state. The average energetic potential of impoundment is calculated with the following formula:

$$E_{avg} = MU \frac{Q^a_{avg}}{10^3} \tag{6}$$

where E_{avg} is the mean energetic potential of the coal slurry deposit (impoundment) in GJ, M estimated mass of coal slurry in the impoundment in Mg, Q^a_{avg} denotes average calorific value of concentrate at analytical state determined in qualitative tests for individual beneficiation method in kJ/kg, U concentrate yield at technological test of beneficiation.

The energetic potential of coal slurries in deposits (impoundments) beneficiated with the use of four methods in comparison with the raw coal slurries energetic potential is presented in Table 2. Due to the fact that methods are not ideal, the loss of energetic potential (S) due to the beneficiation was calculated.

Coal slurry utilization analysis

Analysis of possible utilization paths of coal slurry deposits was performed with the use of the SWOT analysis. The SWOT analysis is a tool to evaluate planned process in order to optimize the strategy of reaching the objective. The main objective of analysis is to identify the current status of the process and its perspective which leads to the best possible strategy. The SWOT analysis takes its name from the abbreviations of the following:

- strengths – characteristics of the project that give it an advantage over others,
- weaknesses – are characteristics that place the project at a disadvantage relative to others,
- opportunities – elements that the project could exploit to its advantage,
- threats – elements that could cause trouble for the project.

The analysis is based on the identification of four group of factors, description if their impact on the further development and management of operations in order to improve the strategy or introduce often radical changes. In the SWOT analysis it is not required to describe and distinguish the factors but to point out key elements on which the analysis is performed. In further stages, a fixed-point scale is established where

Table 2. Energetic potential of raw coal slurry at each deposit (impoundments) and after beneficiation using four methods. The loss of potential is denoted as S

Impoundment		Hydrocyclone				Centrifugal separator, 150 g/l				Reichert spiral separator, 400g/l				Flotation, flotation agent # 2			
	E_{avg}	U	Q_r^{avg}	E_{avg}	S	U	Q^a_{avg}	E_{avg}	S	U	Q^a_{avg}	E_{avg}	S	U	Q^a_{avg}	E_{avg}	S
	GJ	–	kJ/kg	GJ	%	–	kJ/kg	GJ	%	–	kJ/kg	GJ	%	–	kJ/kg	GJ	%
K13	15095667	0,47	18121	8516870	44	0.23	18916	4350680	71	–	–	–	%	–	–	–	–
K14	4693800	0,56	20362	3420816	27	0.36	20654	2230632	52	0.29	18825	5459250	64	–	–	–	–
K12	14812667	0,50	17281	8640500	42	0.10	22042	2204200	85	0.41	20271	2493333	47	–	–	–	–
K18/1	932547	0,50	9295	464750	50	–	–	–	–	0.18	21523	3874140	74	–	–	–	–
K18/2	1007325	0,60	8576	514560	49	–	–	–	–	0.04	21042	92585	90	–	–	–	–
K11/1	8509964	0,51	15990	5219136	39	0.04	21043	538700	94	–	–			–	–	–	–
K3/1	14092825	0,57	16277	12377730	12	0.14	25840	5502369	61	0.15	20760	1992960	77	–	–	–	–
K3/2	2618308	0,63	12027	1333553	49	–	–	–	–	0.23	25843	9040657	36	0.45	24 687	1955210	25
K2	13743987	0,58	14234	9221639	33	0.48	24104	11923600	13	0.06	24258	150564	94	0.41	20 670	9466240	31
K17	3535074	0,44	13444	916880	74	0.03	18965	88187	97	0.50	24335	12602267	9	0.74	27 620	3168014	10
K1	3563810	0,52	17972	1429852	60	0.08	25046	306000	91	0.09	19136	266947	92	0.80	27 120	3319488	7
K4/1	7928525	0,51	24363	4294124	49	0.28	24095	2331625	71	0.14	24241	519000	85	0.81	26 880	7524680	5
K4/2	2577600	0,59	24557	2073136	20	0.47	24164	1851204	28	0.30	24459	2535909	68	0.65	21 525	2280574	11
K4/3	9581173	0,57	25501	6686362	30	0.52	24315	5816148	39	0.50	23763	1936684	25	0.41	24 520	4624472	51
K5/1	1566590	0,46	21415	1180617	25	0.25	24430	793975	49	0.52	24333	5820454	39	–	–		
K5/2	4058928	0,48	21085	2307542	43	0.22	24043	1205997	70	0.30	23352	910728	42	0.58	24 670	3262361	20
K5/3	20566631	0,50	21161	1121533	45	0.26	23802	655983	68	0.27	23666	1456879	64	0.72	25 875	1974780	4
K5/4	2075761	0,51	21844	1136324	45	0.22	24281	544865	74	0.30	24035	764313	63	0.71	25 810	1869160	10
K11/2	3462345	0,44	12008	92999	97	0.02	18519	65187	98	0.27	24195	666330	68	0.70	25 845	3184104	8
K6	4457435	0,47	18022	1999000	55	0.08	24124	455461	90	0.07	18756	231074	93	0.72	25 465	4327013	3
average	–	0,53	16950	–	44	0.22	22846	–	68	0.14	24256	801000	82	0.64	25057	–	15

each element has an attributed value. This method of impact assessment facilitates determination of priority elements in each group. The greatest difficulties are encountered in the assessment of intangible factors where classification is not straightforward. Obviously, the analysis is not free from the subjective assessment of areas which are difficult to group but this can be minimized by public group assessment i.e. external experts or consultants not connected to the project. Commonly, the SWOT analysis is presented in a graphic form (matrix) and as a table. The internal awareness of external strengths and weaknesses of the project is essential for the marketing strategy of the company or a product.

The SWOT analysis regarding the use of coal slurry deposits in the Polish national fuel balance was conducted among ten experts i.e. employees of the Faculty of Mining and Geology of Silesian University of Technology from the Department of Mineral Processing and Waste Utilization and the Institute of Mining Engineering. The group of experts consisted of research assistants, PhD's and professor whose research field and experience was related to waste management, mining engineering and mineral processing. Information and assumptions for the analysis were the same as formulated in the scenarios of innovative hard coal mining waste management technology development (Goralczyk and Lutynski 2012). Assumptions for the SWOT analysis were as follows:

- strengths and weaknesses of coal slurry deposits use in the Polish national fuel balance were characterized by factors related to beneficiation technologies which convert them to a full value fuel,
- opportunities of using these deposits in the Polish national fuel balance are characterized by the factors associated to external conditions,
- threats related to the use of these deposits in the Polish national fuel balance are characterized by the factors associated to the external conditions being an obstacle.

Brainstorming with the expert group allowed identification of factors considered to be important in each of the four groups. These factors are presented below.

STRENGTH

- good identification of coal slurry deposits properties, amount and location
- relatively high calorific value of deposits
- waste (coal slurry) management know-how
- ease of coal slurry processing technology deployment
- low cost of fuel processing
- accessibility to coal slurry deposits
- lack of interest from the coal mines regarding the possibility of coal slurry deposit utilization in the past
- land can be used for other purposes when the processing of deposits (impoundments) is terminated.

WEAKNESS

- considerable variations of coal slurry properties between impoundments
- some variations of coal slurry properties in one deposit

- significant cost of beneficiation plant construction
- low beneficiation efficiency
- high water consumption for the purpose of coal slurry beneficiation,
- limited demand for the obtained fuel
- requirement of land reclamation after depletion of impoundments

OPPORTUNITY

- creation of new work places
- demand for conventional fuels
- depletion of conventional fossil fuels
- location of impoundments on the area where mining technologies are well known
- trend related to waste recycling
- stimulation of activities related to waste management
- actions of local authorities focused on reclamation of post-mining areas
- support by local authorities of actions focused on reclamation of post-mining areas by fiscal and legal policies.

THREAT

- insufficient funding for pro-ecological actions
- limited interest in a beneficiated product
- complex financial procedures of projects related to the use of coal slurry deposits
- appearance of a lobby acting against actions related to the use of coal slurry deposits
- legal restrictions regarding coal slurry deposits management and use of obtained fuel
- strict CO_2 emissions limits
- reluctance of land owners where deposits are located in obtaining permissions for re-use of coal slurries.

The next task was to prioritize identified factors in each group. The experts identified the impact of each factor on the possibility of using coal slurry deposits in the Polish national fuel balance. Three levels of assessment were assumed:

- very high impact – 3 points
- high impact – 2 points
- low impact – 1 point.

The above mentioned prioritization resulted in the weighted average of factor impact on the use of identified coal slurry deposits in the Polish national fuel balance.

Results of SWOT analysis

The results of the SWOT analysis are presented in Table 3. Columns labeled 3,2,1 correspond to the impact rating and indicate the number of experts who chosen particular impact factor on the possibility of using identified coal slurry deposits in Polish national fuel balance.

Table 3. Results of factor prioritization analysis – possibility of using identified coal slurry deposits in Polish national fuel balance

No	STRENGTHS	3	2	1	Average
1	good identification of coal slurry deposits properties, amount and location	4	4	2	2.2
2	relatively high calorific value of deposits	5	4	1	2.4
3	waste (coal slurry) management know-how	3	3	4	1.9
4	ease of coal slurry processing technology deployment	3	4	3	2.0
5	low cost of fuel processing	5	4	1	2.4
6	accessibility to coal slurry deposits	4	4	2	2.2
7	lack of interest from the coal mines regarding the possibility of coal slurry deposit utilization in the past	2	3	5	1.9
8	land can be used for other purposes when the processing of deposits (impoundments) is terminated	4	2	4	2.0
No	WEAKNESSES	3	2	1	Average
1	considerable variations of coal slurry properties between impoundments	1	4	5	1.9
2	some variations of coal slurry properties in one deposit	3	4	3	1.7
3	significant cost of beneficiation plant construction	6	4	0	2.6
4	low beneficiation efficiency	5	3	2	2.5
5	high water consumption for the purpose of coal slurry beneficiation	7	3	0	2.7
6	limited demand for the obtained fuel	4	5	1	2.3
7	requirement of land reclamation after depletion of impoundments	4	4	2	2.1
No	OPPORTUNITIES	3	2	1	Average
1	creation of new work places	4	4	2	2.1
2	demand for conventional fuels	6	3	1	2.7
3	depletion of conventional fossil fuels	6	3	1	2.7
4	location of impoundments on the area where mining technologies are well known,	3	4	3	2.0
5	trend related to waste recycling	4	3	3	2.1
6	stimulation of activities related to waste management	5	5	0	2.5
7	Actions of local authorities focused on reclamation of post-mining areas	3	6	1	2.2
8	support by local authorities of actions focused on reclamation of post-mining areas by fiscal and legal policies	6	4	0	2.6
No	THREATS	3	2	1	Average
1	insufficient funding for pro-ecological actions	7	3	0	2.7
2	limited interest in beneficiated product	2	5	3	1.9
3	complex financial procedures of projects related to the use of coal slurry deposits	4	4	2	2.2
4	appearance of a lobby acting against actions related to the use of coal slurry deposits	5	4	1	2.4
5	legal restrictions regarding coal slurry deposits management and use of obtained fuel	7	3	0	2.7
6	strict CO_2 emissions limits	4	5	1	2.3
7	reluctance of land owners where deposits are located in obtaining permissions for re-use of coal slurries	6	3	1	2.5

Conclusions

Presented beneficiation tests and study of energetic potential show that during the process of coal slurry beneficiation due to the passing of fine coal into the tailing a big share of energetic potential is lost. The most promising results of beneficiation of such coal slurries were obtained for flotation which seems to be evident due to the nature of this process. An average loss of energetic potential was 15% and varied between the impoundments from 3 to 31%. The calorific value on average was 25 057 kJ/kg and was the highest among all tested methods. Unfortunately, this method was ineffective for some of the coal slurries with flotation agents used. The highest loss of energetic potential was observed for beneficiation with centrifugal separator where on average it was 68% and depending on the impoundment varied between 13 to 98%. As it is seen, these are considerable variations which indicate imperfection of the method. The calorific value of the product was on average 22864 kJ/kg which is a good result. These results are similar to the ones obtained with Reichert spiral where the loss of energetic potential was 64% and the average calorific value was 22678 kJ/kg. The lowest calorific value was obtained in case of beneficiation with hydrocyclone classifier-separator. Despite large losses of energetic potential which accounted for 53% the calorific value was on average 16950 kJ/kg and was not considerably larger than that of raw coal slurry i.e. 16427 kJ/kg.

These tests showed that it is possible to beneficiate coal slurry deposits. However, large losses of energetic potential are observed. Moreover, each method requires large quantities of water which increases the cost of operation.

The performed SWOT analysis on the use of identified coal slurry deposits in the national fuel balance revealed factors that may have the highest impact on the utilization of these coal slurries. Taking into account the average priority of the factor impact on the possible use of the identified coal slurries in the national fuel balance which was determined by experts it was assumed that the priority (i.e. above 2.0 points in a three-point scale) have the following.

STRENGTHS: relatively high calorific value of deposits (2.4) and low cost of fuel processing (2.4)

WEAKNESSES: high water consumption for the purpose of coal slurry beneficiation (2.7), significant cost of beneficiation plant construction (2.6), low beneficiation efficiency (2.5), limited demand for the obtained fuel (2.3), requirement of land reclamation after depletion of impoundments (2.1).

OPPORTUNITIES: demand for conventional fuels (2.7), depletion of conventional fossil fuels (2.7), support by local authorities of actions focused on reclamation of post-mining areas by fiscal and legal policies (2.6), stimulation of activities related to waste management (2.5), actions of local authorities focused on reclamation of post-mining areas (2.2), creation of new work places (2.1), trend related to waste recycling (2.1), THREATS: Insufficient funding for pro-ecological actions (2.7), legal restrictions regarding coal slurry deposits management and use of obtained fuel (2.7), reluctance of land owners where deposits are located in obtaining permissions for re-use of coal slurries (2.5), appearance of a lobby acting against actions related to the use of coal slurry deposits (2.4), strict CO2 emissions limits (2.3), complex financial procedures of projects related to the use of coal slurry deposits (2.2)

The obtained results indicate that the internal factors i.e. the ones related to the coal slurry processing technology have much lower impact on the possibility of using coal slurry deposits in national fuel balance. Instead, according to the experts, external factors have much bigger impact and at the same time the number of these factors is larger.

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