Statistical Analysis of Selected Coal Charateristics and Toxic Compounds for FGX Air-Vibrating Separation

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Abstract

Dry beneficiation methods were popular in the first part of the 20th century. In the 1930s, before World War II, dry separators were used more commonly in the United States. Currently, this method is very popular in China, the United States, India, Russia and other places where its implementation is possible. In Poland, by contrast, dry separation still remains uncommon. However, during the last 30 years, dry separators have started to be more commonly used in coal beneficiation. One example of this type of separator might be the FGX air-vibrating separator. This type of separator uses air suspension to separate heavier particles (tailings) from lighter coal grains. The process of dry separation may depend on various parameters, e.g. particle size fraction, air supply, feed parameters, etc.. This paper describes the mathematical model which shows the scope for using this separation method for coal beneficiation. Mathematical models are based on dependencies between calorific value and ash content in the samples tested as well as relations between arsenic, thallium, mercury, lead and other coal characteristics. The latter parameters are of vital importance as Polish emission standards do not have any limits for the elements mentioned above (arsenic, thallium, mercury and lead).

Keywords: *dry separation, FGX dry separator, deshaling, statistical analysis, correlation, mercury, arsenic, thallium, calorific value, ash content*

1. Introduction

Coal preparation is based on many different methods, including the most common one, which is gravity separation (by using jigs, dense medium separators, dense medium cyclones, shaking tables) or a typical physio-chemical method like flotation (commonly used for coking coals). One of the oldest gravity separation methods is dry coal separation using air jigs or air tables. At the beginning of the 20th century, this method was used in the United States (air dense medium suspension created by air and sand in the Frazer-Yancey dry separator). In the 1930s, in the United States, few dry coal separation plants were built. The biggest dry separation plant was established in Lundale West Virginia, and the biggest separator in this plant had a total capacity of 200t/h. At the same time, in Europe, dry separators were used in countries such as Britain (1925), Belgium, Germany or Poland (1928). Dry enrichment is usually implemented in places where there are water shortages for wet beneficiation processes and in a harsh climate due to the possibility of freezing separation products after separation in a water. The raw materials that can go through beneficiation process using this method include mainly hard coals, with a large proportion of coal-fired or waste fractions, and brown coals (hard types) (Mijał & Tora, 2018; Mijał et al, 2019). In Poland, commonly used dry separation equipment includes the FGX air-vibrating separator and OSX optical sorter constructed by the Comex group company (difference in the colours and content of useful material in the tested feed are used for separation). Until now, those machines have not not used in existing coal separation plants (wide tests were conducted on steam and coking coal by Prof. I. Baic and Prof. W. Blaschke's team and the Institute of Mechanized Construction and Rock Mining, and optical separators were tested for pre-concentration of zinc and lead ore, for example).

The last 20 years become a period of fast development for new dry coal beneficiation equipment, especially ADMFB, CFX, TGX, FGX or KAT (Choung et al., 2006; Jambal et al., 2020; Mijał, 2018; Zhenfu et al., 2002). The FGX air-vibrating separator is becoming increasingly popular and is used in the United States, Turkey, India, South Africa, Vietnam, Russia, Mongolia and a dozen other countries (Baic et al., 2014; Baic et al., 2015; Krukowiecki, 1965; Mijał et al., 2018a; 2018b; Wieniewski et al., 2015; Tangshan, 2020). However, in Poland, it still remains uncommon.

Countries like the USA, India or China conduct research to analyse the scope for removing arsenic, mercury, lead and thallium from raw coal. These tests were conducted mostly using the FGX air-vibrating separator (with ADMFB or air jigs) which also shows the potential for using these jigs to remove this kind of contamination (Pan et al., 2020; Dey et al., 2020; Das et al., 2013; Mak et al., 2008; Luttrell et al., 1998; Zhang et al., 2011). Content of calorific value, ash, mercury, lead, thallium and arsenic in coal produced is very important, especially in view of the changes to environmental protection laws in Poland (new emission regulations, changing the quality of produced fossil fuels, implementing new EU regulations etc.). As an example, in Poland, between 2010 and 2014, mercury emission from combustion processes in the energy production and transformation sector alone reached an average amount of around 5,580.52 kg and a total amount(including all emission sources) of 10,014.98 kg. Combustion processes constitute 94% of all mercury emissions (54% of mercury emissions in the power generation sector). In Poland, the content of mercury in hard coal is proven to be between 10 and 800 μg/kg (Bukowski & Burczyk, 2008; Michalska & Białecka, 2012; Smoliński, 2007). Nowadays, in the European Union and Poland, there are currently no regulations concerning emissions of mercury or any other toxic elements. However, over the last few years, EU member states have been obliged to register emission data for the European Pollutant Release and Transfer Register system. This started after the introduction of the Regulation (EC) No 166/2006 of the European Parliament and of the Council (E-PRTR, 2020). In Poland, this kind of emission registration is run by the National Center for Emission Management (Polish: Krajowy Ośrodek Bilansowania i Zarządzania Emisjami – KOBiZE) (Mijal & Tora, 2018).

During the previous few years, some countries, e.g. the Netherlands, the United States or Germany, started implementing some basic regulations for mercury emission. After this, in 2013, the Minamata Convention on Mercury was accepted by some countries including Poland. As a consequence of the introduction of the Convention in the European Union, BAT conclusions have been created for mercury emissions from the combustion of solid fuels (Adamska, 2014; Chmielarz, 2014). Over the last 5 years, more significance has been attached to identifying the occurrence of mercury in raw coal and its beneficiation products (Dziok et al. 2017; 2019). At the same time, other studies focused on the economic scope for using dry coal beneficiation methods in the Polish mining industry (Blaschke & Baic, 2019; Buchalik et al. 2019), which show that dry separation can be applied, providing economic benefits for small private companies. The experiences of some foreign countries prove that investment and operating expenses for dry separation are 48 and 25% lower compared to wet beneficiation methods (Honaker, 2007; Honaker et al., 2010; Honaker et al. 2014) and results prepared by (de Korte, 2010; 2013; 2014) indicate that, when comparing dry separation method with the beneficiation method in dense medium cyclones, the investment and operating expenses can be 25 and 32% lower. Due to the above aspects, e.g. the economic benefits of dry separation and scope for removing mercury using beneficiation methods, this paper aims to describe correlations between different parameters of feed and beneficiation products from the FGX air-vibrating separator (calorific value, ash content, transient moisture, analytical moisture, operating moisture, volatile matter, heating value, coal content, hydrogen content, total sulphur content and mercury content), with a view to increasing the use of this method in Poland. All correlations are described in the next few chapters of this paper.

2. Materials and Methods

Dry beneficiation using an air table works by applying an ever-rising stream of air. A working plate can also get vibration movement to increase the accuracy of separation. The finished product depends on the construction of the table. One example of this type of separators might be the FGX air-vibrating separator. It consists of a funnel feed, dosing feeder, perforated working plate, vibrating element, air chambers, dust removal module and a mechanism that enables the angle of inclination of the working plate and the frequency of vibrations to be changed. The vibrating feeder delivers the feed material to the working plate, inclined at various lateral and longitudinal angles, set in a vibrating motion by means of a vibratory drive (Mijał & Tora, 2018).

In order to provide air supply, there are air chambers under the working plate, which are fed by a centrifugal fan. The fine carbonaceous material forms a fluidized bed (air solid slurry) on contact with the air. As a result, individual grains are similar to each other, depending on size or density. Under the influence of combined forces – air current and vibrations – the coal bed is raised and then, depending on density, it becomes stratified. The lighter material is suspended on the surface of the fluidized bed, while the grains with a higher density sink lie deeper. An additional phenomenon is the liquefaction effect resulting from the interaction of small grains between each other, i.e between the suspension and coarse grains. This phenomenon improves the efficiency of the separation of coarse fractions. Fine material located on the surface of the layer tends to slide over its surface and fall continuously, under the influence of gravity, through the partition at the edge of the plate (dumping of enriched coal). The heavy material falls to the bottom of the layer and is moved towards the waste collection point (gangue) (Baic et al., 2014; Baic et al., 2015; Sobko et al. 2016; Tangshan, 2019).

Air separators have low separation accuracy. This process needs to be conducted strictly following the rules of beneficiation. Other parameters affecting the separation process will only be briefly mentioned in the paper: initial preparation of the feed, grain size & weight feed composition, the amount of air for the separation process, the height of the bars, the angle of the working plate, the number of working plate swings and separation efficiency. Other factors are: total moisture, the dimension of the separated research material, grain size fraction, the amount of grain size fraction (0-6 mm in the feed), the relation between the amount of rock and coal grains in the feed, the total amount of ash in research material and the total amount of middlings in the raw feed. Other specific parameters and of the extent to which grain behaviour depends on the surface of the working board before and during the separation are described in this paper.

The research material used included steam coal extracted from three different coal mines in Poland. The first step was to check the quality of different samples, collected before the separation process (raw feed samples) and after dry beneficiation (concentrate, middlings, tailings or dust samples (the amount of separated product depends on selected parameters of beneficiation process)). All collected samples were subjected to technical and elementary analysis. The mercury content was determined using the MA-2 analyser which uses the atomic spectrometry method. Lead, zinc, copper, nickel and

Tab. 1. Analysis of linear regression between calorific value and ash content in the feed – Experiment 1

Tab. 1. Analiza regresji liniowej dla wartości opałowej i zawartości popiołu w nadawie – Eksperyment 1

N=12	Summary of regression of dependent variable: Q_{uF} R= 0.92914195 R^2= 0.86330475 Adjusted R^2= 0.84963523 F(1,10)=63.155 p<0.00001 Standard error of estimation: 564.22					
	b*	Standard error from b*	b	Standard error from b	t(10)	p
Constant term			29265.17	1626.577	17.99187	0.000000
A_F	-0.929142	0.116917	-340.52	42.849	-7.94704	0.000012

where: N – quantity of the sample; b – value of parameter; b* – value of parameter of normalised distribution; t – value of t-Student test; p – significance level; R – correlation index; R^2 – coefficient of determination; F – value of F-Snedecor test.

Tab. 2. Analysis of linear regression between calorific value and ash content in concentrate – Experiment 1

Tab. 2. Analiza regresji liniowej dla wartości opałowej i zawartości popiołu w koncentracie – Eksperyment 1

N=12	Summary of regression of dependent variable: Q_{uC} R=0.83327499 R^2= 0.69434720 Adjusted R^2= 0.66378192 F(1,10)=22.717 p<0.00076 Standard error of estimation: 660.50					
	b*	Standard error from b*	b	Standard error from b	t(10)	p
Constant term			26876.63	1428.484	18.81480	0.000000
A_C	-0.833275	0.174829	-255.87	53.684	-4.76622	0.000761

Tab. 3. Analysis of linear regression between calorific value and ash content in middlings – Experiment 1

Tab. 3. Analiza regresji liniowej dla wartości opałowej i zawartości popiołu w produkcie pośrednim – Eksperyment 1

N=12	Summary of regression of dependent variable: Q_{uM} R= 0.94597279 R^2= 0.89486451 Adjusted R^2= 0.88435096 F(1,10)=85.115 p<,00000 Standard error of estimation: 1405.4					
	b*	Standard error from b*	b	Standard error from b	t(10)	p
Constant term			29263.37	1806.529	16.19867	0.000000
A_M	-0.945973	0.102536	-342.66	37.142	-9.22580	0.000003

Tab. 4. Analysis of linear regression between calorific value and ash content in tailings – Experiment 1

Tab. 4. Analiza regresji liniowej dla wartości opałowej oraz zawartości popiołu w odpadach – Eksperyment 1

N=12	Summary of regression of dependent variable: Q_{uT} R= 0.98843110 R^2= 0.97699604 Adjusted R^2= 0.97469564 F(1,10)=424.71 p<0.00000 Standard error of estimation: 259.04					
	b*	Standard error from b*	b	Standard error from b	t(10)	p
Constant term			27839.13	1235.573	22.5314	0.000000
A_T	-0.988431	0.047962	-319.00	15.479	-20.6084	0.000000

Tab. 5. Analysis of linear regression between calorific value and ash content – Experiment 2

Tab. 5. Analiza regresji liniowej dla wartości opałowej i zawartości popiołu – Eksperyment 2

N=48	Summary of regression of dependent variable: Q_u= 0.91782903 R^2= 0.84241012 Adjusted R^2= 0.83898426 F(1,46)=245.90 p<0.0000 Standard error of estimation: 2904.4					
	b*	Standard error from b*	b	Standard error from b	t(46)	p
Constant term			27627.92	1046.856	26.3913	0.000000
A	-0.917829	0.058531	-314.67	20.067	-15.6811	0.000000

Tab. 7. Analysis of linear regression between arsenic content in middlings and mercury content in concentrate – Experiment 3

Tab. 7. Analiza regresji liniowej dla zawartości arsenu i zawartości rtęci w koncentracie – Eksperyment 3

N=5	Summary of regression of dependent variable: MAstd (data dry separation 2) R= 0.88757252 R^2= 0.78778499 Adjusted R2= 0.71704665 F(1,3)=11.,137 p<0.04448 Standard error from estimation 3.5230					
	b*	Standard error from b*	b	Standard error from b	t(3)	p
Constant term			-1.20900	3.494465	-0.345976	0.752202
CHg_t^d	0.887573	0.265967	0.11314	0.033904	3.337155	0.044482

Tab. 6. List of parameters included in the Experiment 3

Tab. 6. Lista parametrów mierzonych w Eksperymencie 3

Parameter	**Index**	**Unit**
Transient moisture	W_{ex}^{r}	%
Analytical moisture	W_a	%
Operating moisture	W_t^{r}	%
Ash content	A_a	%
Volatile matter	V^{daf}	%
Calorific value	Q_s^{a}	kJ/kg
Heating value	Q_i^{a}	kJ/kg
Coal content	C^{daf}	%
Hydrogen content	H^{daf}	%
Total sulphur content	S_t^{d}	%
Mercury content	Hg_t^{d}	μg/kg

chromium content was assessed by flame atomisation spectrometry (FAAS), and arsenic content by graphite cuvette atomisation (GFAAS). The Hitachi Z-2000 tandem spectrometer with Zeeman background correction was used for these determinations (Makowska et al., 2017). Other parameters were marked in accordance with PN-ISO standards applicable in Poland.

The first stage (Experiment 1) was based on samples divided into 12 feeds, 12 concentrates, 12 middlings and 12 tailings ones, and the minimum total weight of one sample used for the test was 25 Mg. Each sample had a different calorific value (Qu) and ash content (Ar). What is more, difficulties affecting the coal separation process also differed (it was difficult to obtain small samples for the research).

The samples used in phase 1 of the experiment might be considered as not applicable, but for the purpose of this research and discussion, their comparison by analysing correlation between calorific value (Qu) & ash content (Ar) was carried out. After this comparison of results, a theoretical mathematical equation defining the relation between calorific value (Qu) and ash content (Ar) during the dry separation process was developed. This can be treated as an introduction to the further research into the issue of dry coal separation efficiency. Secondly, the whole set of samples was used, but this time without dividing them into subproducts (48 samples, Experiment 2). Next, the mathematical model for the whole experiment was developed. Finally, arsenic, thallium and lead content were taken into account. One reason for this was that these elements had never been analysed using FGX methods in Poland before. Another reason is that emission norms for the aforementioned materials varied, thus relations with each product (feed, concentrate, middlings and tailings) were examined separately.

Furthermore, in 2017, the European Union adopted the IED Directive (Industrial Emission Directive), which contained the relevant BAT conclusions (Best Available Techniques) for emission limits for big power plants and other industrial factories. The BAT conclusions will be implemented in 2021. This creates the need to forecast the amount of the additional substances occurring in mineral products, including those presented in the paper. It will enable the clean coal to be obtained from the FGX dry separation process concerning the quality of the final beneficiation product.

The statistically significant models presented are result of the analysis.

3. Results and Discussion

3.1. Calorific value and ash content

Statistical methods in the processing of mineral resources are used to analyse experiments results. The possible main purposes of these works are to assess the enrichment of the raw material, to study the mechanism of phenomena occurring during processing, to assess process characteristics, to prepare nomograms and charts and to study the properties of new devices, etc (Foszcz et al., 2016; Marciniak-Kowalska et al., 2014; Tumidajski & Saramak, 2009; Niedoba, 2013; Niedoba et al., 2020; Öney et al. 2019; 2020).

The Authors selected one characteristic which proved to be a suitable basis for creating a theoretical mathematical model for dry separation. Concerning two first phases of the experiment, the main parameters taken into consideration were calorific value and ash content in raw feed and beneficiation products. The parameters mentioned and described in this chapter are described below:

- AF – ash content in the feed,
- QuF – calorific value in the feed,
- AC – ash content in concentrate,
- QuC – calorific value in concentrate,
- AM – ash content in middlings,
- QuM – calorific value in middlings,
- AT – ash content in tailings,
- QuT – calorific value in tailings.

Mathematical models were created for calorific value. To create these models, two experiments were taken into consideration. One consisted of 12 samples for which 4 models were created separately, for the feed, concentrate, middlings and tailings. The second experiment consisted of 48 samples, and the model created included the whole sample, without division of the products.

Looking at the results of correlation indices between calorific values and ash contents for experiment 1, one can observe that values of these indices for all products are high. The lowest results were achieved for the concentrate; nonetheless, their value is statistically significant. The same observations were established for experiment 2. The presented models enabled regressive models to be created. These are presented in Tables 1-5 and equations 1-5.

$$Q_{uf} = -340.52A_f + 29265.17; \quad R^2=86,33\% \qquad (1)$$

Tab. 8. Analysis of linear regression between lead content in middlings and transient moisture in concentrate – Experiment 3

Tab. 8. Analiza regresji liniowej dla zawartości ołowiu w produkcie pośrednim oraz wilgotnością przejściową w nadawie – Eksperyment 3

N=5	Summary of regresion of dependent variable: MPbtd (data dry separation 2) R= 0.92561196 R^2= 0.85675750 Adjusted R2= 0.80901000 F(1,3)=17.944 p<0.02408 Standard error from estimation: 3.1451					
	b*	Standard error from b*	b	Standard error from b	t(3)	p
Constant term			5.156418	2.769023	1.862180	0.159485
CW_{ex}^{r}	0.925612	0.218512	2.971642	0.701524	4.235977	0.024081

Tab. 9. Analysis of linear regression between thallium content in tailings and analytical moisture in feed – Experiment 3

Tab. 9. Analiza regresji liniowej dla zawartości talu w odpadach oraz wilgotności analitycznej w nadawie – Eksperyment 3

N=6	Summary of regresion of dependent variable: TTltd (data dry separation 2) R= 0.95372004 R^2= 0.90958192 Adjusted R2= 0.88697740 F(1,4)=40.239 p<0.00316 Standard error from estimation: 0.12609					
	b*	Standard error from b*	b	Standard error from b	t(4)	p
Constant term			0.464575	0.087915	5.284351	0.006152
FW^{a}	0.953720	0.150348	0.117426	0.018512	6.343417	0.003163

Tab. 10. Analysis of linear regression between lead content in tailings and analytical moisture in feed – Experiment 3

Tab. 10. Analiza regresji liniowej dla zawartości ołowiu w odpadach oraz wilgotności analitycznej w nadawie – Eksperyment 3

N=6	Summary of regresion of dependent variable: TPbtd (data dry separation 2) R= 0.96334551 R^2= 0.92803456 Adjusted R2= 0.91004320 F(1,4)=51.582 p<0.00199 Standard error from estimation: 3.7572					
	b*	Standard error from b*	b	Standard error from b	t(4)	p
Constant term			6.314377	2.619664	2.410376	0.073525
FW^{a}	0.963346	0.134132	3.961634	0.551600	7.182078	0.001991

Tab. 11. Analysis of linear regression between thallium content in tailings and analytical moisture in concentrate – Experiment 3

Tab. 11. Analiza regresji liniowej dla zawartości talu w odpadach oraz wilgotności analitycznej w koncentracie – Eksperyment 3

N=6	Summary of regresion of dependent variable: TTltd (data dry separation 2) R= 0.99009633 R^2= 0.98029074 Adjusted R2= 0.97536342 F(1,4)=198.95 p<0.00015 Standard error from estimation: 0.05887					
	b*	Standard error from b*	b	Standard error from b	t(4)	p
Constant term			0.265597	0.052041	5.10364	0.006965
CW^{a}	0.990096	0.070195	0.142052	0.010071	14.10497	0.000147

Tab. 12. Analysis of linear regression between thallium content in tailings and total sulphur content in concentrate – Experiment 3

Tab. 12. Analiza regresji liniowej dla zawartości talu w odpadach oraz całkowitej zawartości siarki w koncentracie – Eksperyment 3

N=6	Summary of regresion of dependent variable: TTltd (data dry separation 2) R= 0.92876633 R^2= 0.86260690 Adjusted R2= 0.82825863 F(1,4)=25.114 p<0.00743 Standard error from estimation: 0.15543					
	b*	Standard error from b*	b	Standard error from b	t(4)	p
Constant term			-0.793805	0.347168	-2.28651	0.084180
CS_{t}^{d}	0.928766	0.185333	1.826127	0.364399	5.01134	0.007431

Tab. 13. Analysis of linear regression between lead content in taillings and operating moisture in concentrate – Experiment 3

Tab. 13. Analiza regresji liniowej dla zawartości ołowiu w odpadach oraz wilgotności operacyjnej w koncentracie – Eksperyment 3

N=6	Summary of regresion of dependent variable: TPbtd (data dry separation 2) R= 0.97641336 R^2= 0.95338305 Adjusted R2= 0.94172882 F(1,4)=81.806 p<0.00083 Standard error from estimation: 3.0239					
	b*	Standard error from b*	b	Standard error from b	t(4)	p
Constant term			-0.936800	2.777474	-0.337285	0.752858
CW_{t}^{r}	0.976413	0.107955	2.974026	0.328816	9.044651	0.000828

$$Q_{uc} = -255.87A_c + 26876.63;\ R^2=69.43\% \tag{2}$$

$$Q_{uM} = -342.66AM + 29263.37;\ R^2=89.49\% \tag{3}$$

$$Q_{uT} = -319.00AT + 27839.13;\ R^2=97.70\% \tag{4}$$

$$Q_u = -314.67A + 27627.92;\ R^2=84.24\% \tag{5}$$

Earlier studies have shown that it is not possible to assume a constant heat loss per 1% increase of ash content for various coals (Blaschke & Baic, 2020). The above-mentioned relationships show that using dry deshaling, as well as other beneficiation methods, will produce different effects. Results depend on the characteristics of the relationship between the calorific value and ash content of the specific type of coal being tested. The models obtained make it possible to establish whether the increase in calorific value is related mainly to the reduction of gangue content in the material, or whether the reduction of the value is low, which may be caused by incorrect separation parameters adopted before starting the process. If a significant relationship between the ash content and the calorific value is found, it can be concluded that the methodology of dry beneficiation adopted when using the FGX is accurate. Otherwise, the coal should be enriched using "wet" technology.

3.2. Arsenic, thallium, mercury and lead content in selected products of dry coal separation

As a basis for models, correlation matrices were created. Because of the size of the matrix, it was divided into subsections. Table 6 presents the list of parameters included in the analysis.

The following statistically important models (Tables 7-19; equations 6-18) were developed on the basis of correlation indices between arsenic, thallium and lead content as well as other characteristics of the samples. Notably, due to the small number of samples, only part of the relations are significant.

Concerning arsenic, only one correlation, observed in middlings, was significant. Other products did not show high correlation indices for arsenic content. Thus, one might say that it does not really correlate with other material characteristics; therefore, it is difficult to predict its content in the type of coal being tested. As far as other components are concerned, results showed that the most important relations included middlings, tailings and concentrates. Surprisingly, not so many relations were found for feed. Considering the components examined, the most statistically important equations were found for thallium, especially in the case of tailings.

It was also noteworthy that a significant number of relations were observed for lead content in tailings. This means that these components can be easier described by other characteristics of coal, especially when it has already been processed and divided into sub-products. However, a larger number of samples included in further experiments may assist in carrying out a more detailed analysis, and even some weaker relations may prove significant.

$$MAs_t^d = 0.11314\ CHg_t^d - 1.20900;\ R^2=78.78\% \tag{6}$$

$$MPb_t^d = 2.971642\ CW_{ex}^r + 5.156418;\ R^2=85.67\% \tag{7}$$

$$TTl_t^d = 0.117426\ FW^a + 0.464575;\ R^2=90.96\% \tag{8}$$

$$TPb_t^d = 3.961634\ FW^a + 6.314377;\ R^2=92.80\% \tag{9}$$

$$TTl_t^d = 0.142052\ CW^a + 0.265597;\ R^2=98.03\% \tag{10}$$

$$TTl_t^d = 1.826127\ CS_t^d - 0.793805\ ;\ R^2=92.88\% \tag{11}$$

$$TPb_t^d = 2.974026\ CW_t^r - 0.936800;\ R^2=97.64\% \tag{12}$$

$$TPb_t^d = 60.3096\ CS_t^d - 34.9234;\ R^2=84.34\% \tag{13}$$

$$TTl_t^d = 0.136645\ MW^a + 0.331830;\ R^2=96.87\% \tag{14}$$

$$TTl_t^d = -0.031248\ MA^a + 1.806443;\ R^2=86.44\% \tag{15}$$

$$TTl_t^d = 0.00011\ MQ_s^a - 1.38258;\ R^2=88.29\% \tag{16}$$

$$TPb_t^d = 4.545630\ MW^a + 2.115580;\ R^2=96.10\% \tag{17}$$

$$TPb_t^d = 0.0037\ MQ_s^a - 52.2748;\ R^2=81.71\% \tag{18}$$

The occurrence of the elements selected depends mainly on the form of their presence in the raw material used. For example, in the case of mercury, it may be removed when coal contains high amount of pyrite. Then, the efficiency of mercury removal oscillates within the limits of 90%. If there is a smaller amount of pyrite in the material then this level of efficiency decreases to approximately 10%. Another important factors is whether the form of pyrite is organic or mineral. If it is organic, then it is necessary to apply additional chemical or biological methods to the process (Blaschke & Baic, 2020).

As far as arsenic, lead and thallium are concerned, it should be noted that all of them are considered ecotoxic elements; therefore, their presence in coal is undesirable. In the case of Poland, the current production of energy – around 80% of all energy produced – is still based on coal combustion . The emission of these elements into the atmosphere can be lowered by introducing what is called pre-combustion processes, which include a type of mechanical processing that enables coal to be separated from the other particles. If the particles are pyrite, such processing is much easier; otherwise, more complicated expensive chemical or biological methods need to be used. Apart from mercury, this mainly applies to arsenic and lead; the analysis showed that these elements could be removed from the coal material, especially when they occurred in pyrite. As far as thallium is concerned, more research needs to be conducted in the future.

The models presented could be more statistically significant if the number of samples were larger. Observations based on the models presented can be used to forecast both the quality of the coal used in a power plant as well as selecting the appropriate beneficiation method. It also shows that the presence of additional elements in the material being analysed can influence the quality of the coal, measured by calorific value or analytic moisture (e.g., the presence of thallium). Furthermore, in Poland, the FGX method is still not common but could be effectively introduced in some cases. Statistical analysis would make such applications more justifiable.

Tab. 14. Analysis of linear regression between lead content in tailings and total sulphur content in concentrate – Experiment 3

Tab. 14. Analiza regresji liniowej dla zawartości talu w odpadach oraz wilgotności analitycznej w produkcie pośrednim – Eksperyment 3

N=6	Summary of regresion of dependent variable: TPbtd (data dry separation 2) R= 0.91836434 R^2= 0.84339306 Adjusted R2= 0.80424133 F(1,4)=21.542 p<0.00972 Standard error from estimation: 5.5425					
	b*	Standard error from b*	b	Standard error from b	t(4)	p
Constant term			-34.9234	12.37971	-2.82102	0.047779
CS_t^d	0.918364	0.197868	60.3096	12.99413	4.64130	0.009725

Tab. 15. Analysis of linear regression between thallium content in taillings and analytical moisture in middlings – Experiment 3

Tab. 15. Analiza regresji liniowej dla zawartości talu w odpadach oraz wilgotności analitycznej w produkcie pośrednim – Eksperyment 3

N=5	Summary of regresion of dependent variable: TTltd (data dry separation 2) R= 0.98425066 R^2= 0.96874936 Adjusted R2= 0.95833248 F(1,3)=92.998 p<0.00237 Standard error from estimation: 0.08422					
	b*	Standard error from b*	b	Standard error from b	t(3)	p
Constant term			0.331830	0.073813	4.495573	0.020545
MW^a	0.984251	0.102063	0.136645	0.014170	9.643549	0.002367

Tab. 16. Analysis of linear regression between thallium content in tailings and ash content in middlings – Experiment 3

Tab. 16. Analiza regresji liniowej dla zawartości talu w odpadach oraz zawartości popiołu w produkcie pośrednim – Eksperyment 3

N=5	Summary of regresion of dependent variable: TTltd (data dry separation 2) R= 0.92970543 R^2= 0.86435219 Adjusted R2= 0.81913625 F(1,3)=19.116 p<0.02214 Standard error from estimation: 0.17547					
		Standard b*error from b*	b	Standard error from b	t(3)	p
Constant term			1.806443	0.212292	8.50925	0.003409
MA^a	-0.929705	0.212640	-0.031248	0.007147	-4.37220	0.022135

Tab. 17. Analysis of linear regression between thallium content in tailings and calorific value in middlings – Experiment 3

Tab. 17. Analiza regresji liniowej dla zawartości talu w odpadach oraz wartości opałowej dla produktu pośredniego – Eksperyment 3

N=5	Summary of regresion of dependent value: TTltd (data dry separation 2) R= 0.93961963 R^2= 0.88288505 Adjusted R2= 0.84384674 F(1,3)=22.616 p<0.01765 Standard error from estimation: 0.16304					
	b*	Standard error from b*	b	Standard error from b	t(3)	p
Constant term			-1.38258	0.494631	-2.79517	0.068126
MQ_s^a	0.939620	0.197581	0.00011	0.000024	4.75561	0.017648

Tab. 18. Analysis of linear regression between lead content in tailings and analytical moisture in middlings – Experiment 3

Tab. 18. Analiza regresji liniowej dla zawartości ołowiu w odpadach oraz wilgotności analitycznej w produkcie pośrednim - Eksperyment 3

N=5	Summary regresion of dependent value: TPbtd (data dry separation 2) R= 0.98031244 R^2= 0.96101249 Adjusted R2= 0.94801665 F(1,3)=73.948 p<0.00331 Standard error from estimation: 3.1419					
	b*	Standard error from b*	b	Standard error from b	t(3)	p
Constant term			2.115580	2.753624	0.768289	0.498254
MW^a	0.980312	0.113999	4.545630	0.528605	8.599286	0.003306

Tab. 19. Analysis of linear regression between lead content in tailings and calorific value in middlings – Experiment 3

Tab. 19. Analiza regresji liniowej dla zawartości ołowiu oraz wartości opałowej w produkcie pośrednim – Eksperyment 3

N=5	Summary regresion of dependent value: TPbtd (data dry separation 2) R= 0.90392637 R^2= 0.81708288 Adjusted R2= 0.75611051 F(1,3)=13.401 p<0.03523 Standard error from: 6.8054					
	b*	Standard error from b*	b	Standard error from b	t(3)	p
Constant value			-52.2748	20.64634	-2.53192	0.085281
MQ_s^a	0.903926	0.246926	0.0037	0.00100	3.66072	0.035227

4. Conclusions

Based on the calculations performed for all experiments mentioned in this paper, it was found that there are high correlations between heating values and ash content. This means that it is possible to predict the calorific value of a coal sample by establishing its ash content. The dry coal separation method used in these experiments indicated that it can be an effective tool for separating feedstock into sub-products (concentrate, middlings, and tailings), and with the help of models, it is easier and more effective to select the appropriate tool or technique. Regarding arsenic, thallium, lead, and mercury – elements that have not previously been considered for the FGX dry separation method – few correlations were found to be statistically significant. However, relatively high quality models include thallium content, especially for tailings. The most difficult thing to predict is arsenic content but this situation may improve if more analyses of this kind are performed. This may help to find less correlated and more significant relationships between the carbon characteristics of all considered products, while more complex models may help to describe the problem more accurately.

The number of samples included in this paper was not sufficient to conclude that the results were representative of all circumstances. These samples were prepared specifically for the evaluation of the FGX dry separation method. If more samples with more variable process conditions were available, the results would enable the process to be defined more accurately. However, this particular method is still not common in Poland and therefore requires much more research.

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To memory of Prof. Wiesław Blaschke (R.I.P. 23.02.2021)

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Analiza statystyczna wybranych charakterystyk i składników toksycznych węgla dla procesu separacji w separatorze powietrznym FGX

Suche metody wzbogacania były popularne w pierwszej połowie XX wieku. Separatory suche były używane zwłaszcza przed II Wojną Światową w latach 30-ych w USA. Obecnie, metoda ta jest bardzo popularna w Chinach, USA, Indiach, Rosji oraz w innych miejscach, gdzie możliwe jest jej zastosowanie. W Polsce proces ten jest wciąż bardzo mało popularny. Podczas ostatnich 30 lat systemy wzbogacania węgla zaczęły szerzej korzystać z separatorów suchych a przykładem bardzo popularnego urządzenia tego typu jest FGX – wibracyjny stół powietrzny. Ten typ separatora korzysta z zawiesiny powietrznej w celu wydzielenia cięższych ziaren (odpadów) od lżejszych ziaren węgla. Sucha separacja może zależeć od różnych parametrów, tj. klasa ziarnowa, zasoby powietrza, parametry nadawy itp. Artykuł ten opisuje model matematyczny, który pokazuje możliwości zastosowania tej metody separacji przy wzbogacaniu węgla. Modele matematyczne oparte były na zależnościach pomiędzy wartością opałową oraz zawartością popiołu w testowanych próbkach, jak również na relacjach pomiędzy zawartościami arsenu, talu, rtęci, ołowiu i innych charakterystyk węgla. Ostatnie parametry są bardzo ważne ponieważ polskie standardy emisji nie zawierają limitów dla pierwiastków wymienionych powyżej, a więc arsenu, talu, rtęci oraz ołowiu.

Słowa kluczowe: *separacja sucha, suchy separator FGX, odkamienianie, analiza statystyczna, korelacja, rtęć, arsen, tal, wartość opałowa, zawartość popiołu*