Mathematical model of dry coal deshaling by using FGX vibrating air table

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Abstract. Dry coal separation process is a relatively new method for coal separation in Poland. First air separators which were used on bigger scale was in United States before Second World War in 1930s. Nowadays is widely used in China, United States, Russia and all those places where access to water is limited. Last year’s very popular become separation by using vibrating air tables FGX where beneficiation process use air suspension which separate heavier particles from light coal grains. This separation process depends on different parameters like preparation of feed and it parameters, grain size fraction, air supply etc.. This paper will describe what is it a dry coal separation, modern separation techniques and in the main part focus on creating mathematical model which will present the quality of using this kind of process for coal deshaling. Mathematical model will base on dependence between calorific value and ash content in the tested samples.

1. Introduction
Coal preparation is based on many different methods like the most common gravity separation (by using jigs, dense medium separators, dense medium cyclones, shaking tables or typical physio-chemical method like flotation (commonly used for coking coals). One of old gravity separation methods is dry coal separation by using air jigs or air tables. In the beginning of 20th century this method was used in United States (air dense medium suspension created by air and sand in Frazer-Yancey dry separator). In 1930s in United States build few dry coal preparation plants. The biggest dry separation plant was in Lundale West Wirginia, the biggest separator in this plant had total capacity 200t/h. In the same time in Europe dry separation where used by countries such as England (1925), Belgium, Germany or Poland (1928). Dry enrichment is usually applied in places where there are water shortages to wet processes and in a harsh climate due to the possibility of freezing separation products after separation in a water medium. The raw materials that can be enriched with this method are mainly hard coals with a large proportion of coal-fired or waste fractions and for brown coals (hard types). In Poland common dry separation equipment is FGX air vibrating table and OSX optical sorter constructed by Comex group company (for separation are used difference in colours and content of
usefull material inside tested feed). Those machines till this moment was not applied into existed coal preparation plants (wide tests were conducted on steam and coking coal by the team headed by Prof. I. Baic and W. Blaschke and Institute of Mechanized Construction and Rock Mining, optical separators was tested for example for pre-concentration of zinc and lead ore).

Last 20 years become a very fast developing time of new equipment for dry coal enrichment especially in China (CFX, TGX or FGX). Very popular become air vibrating table type FGX which is used in United States, Turkey, India, South Africa, Vietnam, Russia, Mongolia and a dozen other countries [1, 2, 3, 4, 5, 7, 8, 9, 11].

2. Dry deshaling principles
Dry beneficiation on air table work by using ever-rising stream of air. Work plate can also get vibration movement to increase the accuracy of separation. Receipt of products depends on construction of table. As an example of this type of separators is air vibrating table FGX. Second type of air separators are air jigs. The air is fed by pulsation under the material layer. The material is separated in the same way as during wet enrichment in a water jig. The raised material is loosening, and grains differing in density from each other begin to form layers of grains of the same density. Vibrating air separator FGX consists of a funnel feed, dosing feeder, perforated work plate, vibrator, air chambers, dust removal module and a mechanism that allows to change the angle of inclination of the working plate and the frequency of vibrations. On the installation using a vibratory feeder a feed is fed which goes to a working plate inclined at various lateral and longitudinal angles set in a vibrating motion by means of a vibratory drive [13].

In order to ensure air supply under the working plate there are air chambers, which are fed by a centrifugal fan. The fine carbon material forms a fluidized bed (air-solid slurry) as a result of contact with air. As a result individual grains can fall relative to each other depending on their size or density. Under the influence of combined forces: air current and vibrations the coal bed is raised and then depending on the density it becomes stratified. The lighter material is suspended on the surface of the fluidized bed and the grains with a higher density sink deeper. An additional phenomenon is the liquefaction effect resulting from the interaction of small grains between them, which is a 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). Figure 1 shows the distribution on FGX working plate [4, 5, 6, 7, 8, 11, 13].
Previously mentioned scientific team lead other research to show possibilities of the applicability of FGX vibrating air table as a good solution to remove sulfur [16, 17], mercury [18, 19, 20, 21, 22, 23] or they are working on the application of this method as a supplement to the enrichment technology in jigs (initial averaging of feed using dry deshaling) [24, 25].

3. Parameters influencing the separation on the air table separator

Air separators have low separation accuracy. This process need to be conducted with strictly followed rules of enrichment. The separation process depends on many parameters [14, 15]:

- **Initial preparation of the feed** – with the low coefficient of equal fallen grains to separation process should be send narrow grain classes for example 50-25 mm or 25-6 mm etc.. Industry experience show that it is also possible to send for beneficiation process grains with size 80(75)-0 mm or 50-0 mm. Very necessary during separation process is to keep in the main fee
the amount of small grains between 15 and 30%. Those grains are necessary to not lose the important static pressure (before it change into dynamic pressure).

- **Grain size & weight feed composition** – sometimes during separation processes in processing plants are separated even grains with maximum size 100 mm. Grain size smaller than 0.8 (0.5) mm is not separated. Feed with high amount of middlings is also not good for separation process. In situations where is a lot of middlings it should be changed classification scale,

- **Amount of air for separation process** – this parameter is define by tests. If the feed have high amount of grains with big size and high humidity, thicker feed layer which is send to separation process the amount of air for separation process should be bigger,

- **Height of the bar** – this parameter it is chosen during separation process and depend on grain size of the feed and difficulty of enrichment process. Bars can be divided into two types: bar of working plate and edge bars. Edge bars control the layer of material which is on working plate and time for remove concentrate from separator. Working plate bars control the evenly distribution of the material at working plate surface,

- **Angle of working plate** – longitudinal angle affect the time of separation the wastes, middlings and wastes from feed. With increasing the longitudinal angle the time of separation wastes will be too short and wastes affect the quality of separated concentrates. Too low longitudinal angle will create the chance of losing useful minerals in waste fraction. In practical way the longitudinal angle can be changed between 0 – 2°. The transverse angle affect the separation time of concentrate. Low transverse angle cause longer time of separation of the feed at surface of working plate which affect separation efficiency. In practical way the transverse angle can be changed between 0 – 10°.

- **Number of working plate swings** – amount of swings depend on amount of waste fraction and humidity of the feed. With high amount of swings the separation process of wastes will increase. It is recommended to choose the about of swings which depends on longitudinal angle of working plate. The total amount of swings per minute should be between 200 to 450.

- **Separator efficiency** – the optimal efficiency of separator is determine experimentally. Most important factors are grain size of material, weight composition of feed and total amount of humidity in the feed.

Experience described by foreign users shows that separation process also depends on factors mentioned below [14, 15]:

- Total moisture,
- Dimension of the separated research material (maximum grains),
- Grain size fraction,
- Amount of grain size fraction 0 – 6 mm in the feed,
- Relation between amount of rock and coal grains in the feed,
- Total amount of ash in research material,
- Total amount of middlings in raw feed.

Other specific parameters and dependence of grain behavior on the surface of the working board and during the separation are described in this paper [26].

4. **Characteristic of the research material**
Research material was a steam coal from three different coal mines located in Poland (in total 12 samples). Total minimum weight of one sample used for test was 25 Mg, each sample was different to another by calorific value \( Q_m \), ash content \( A \), or difficulties with coal separation process were different between samples.
In practical way comparing of those samples should not be applicable but for this paper and discussion we compare them by making correlation between calorific value $Q_u$ & ash content $A_r$. After this comparison of results it will be created a theoretical mathematical equation which is define dependence calorific value $Q_u$ and ash content $A_r$ during dry separation process. This paper will be introduction to the further research over the issue of dry coal separation efficiency.

5. Results
From many published papers about dry coal separation in Poland and new vibrating air table separator was chosen some of important data which show the effects of deshaling etc.. Based on data published by team of Prof. Blaschke & Prof. Baic in Polish and foreign journals and descriptions about working principles of FGX vibrating air table and parameters which can affect the efficiency of beneficiation process we choose one characteristic which was very good base to create theoretical mathematical model of dry separation [1, 3, 4, 7, 10, 11, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. The main parameters taken for consideration were calorific value and ash content in raw feed and beneficiation products. Parameters mentioned and described in this chapter are widely described below:

- $A_F$ – ash content in the feed,
- $Q_{uF}$ – calorific value in the feed,
- $A_C$ – ash content in concentrate,
- $Q_{uC}$ – calorific value in concentrate,
- $A_M$ – ash content in middlings,
- $Q_{uM}$ – calorific value in middlings,
- $A_T$ – ash content in tailings,
- $Q_{uT}$ – 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. Second experiment consisted of 48 samples and the model was created generally for the whole sample, without partition of the products. Correlation matrices for both experiments are presented in Tables 1 and 2 and the occurring regressive models are positioned in Tables 3-7.

Table 1. Correlations between calorific value and ash content chosen for this research.

| Variable | Mean value | Standard deviation | $A_F$ | $Q_{uF}$ | $A_C$ | $Q_{uC}$ | $A_M$ | $Q_{uM}$ | $A_T$ | $Q_{uT}$ |
|----------|------------|-------------------|-------|----------|-------|----------|-------|----------|-------|----------|
| $A_F$    | 37.77      | 3.970             | 1.000000 | -0.929142 | -0.566224 | -0.302790 | 0.084312 | -0.007712 | 0.566836 | -0.566194 |
| $Q_{uF}$ | 16403.67   | 1455.044          | -0.929142 | 1.000000 | -0.549374 | 0.392021 | 0.063238 | -0.104686 | -0.478539 | 0.508491 |
| $A_C$    | 26.37      | 3.710             | 0.566224 | -0.549374 | 1.000000 | -0.833275 | -0.072375 | 0.026067 | 0.597012 | -0.545218 |
| $Q_{uC}$ | 20129.08   | 1139.093          | -0.302790 | 0.392021 | -0.833275 | 1.000000 | -0.059140 | 0.089404 | -0.169609 | 0.126256 |
| $A_M$    | 47.40      | 11.409            | 0.084312 | 0.063238 | -0.072375 | -0.059140 | 1.000000 | -0.945973 | -0.102543 | 0.118924 |
| $Q_{uM}$ | 13022.42   | 4132.623          | -0.007712 | -0.104686 | 0.026067 | 0.089404 | -0.945973 | 1.000000 | 0.146318 | -0.155608 |
| $A_T$    | 79.68      | 5.046             | 0.566836 | -0.478539 | 0.597012 | -0.169609 | -0.102543 | 0.146318 | 1.000000 | -0.988431 |
| $Q_{uT}$ | 2422.58    | 1628.446          | -0.566194 | 0.508491 | -0.545218 | 0.126256 | 0.118924 | -0.155608 | -0.988431 | 1.000000 |
Table 2. General correlations between calorific value and ash content.

Marked correlation indexes are significant with \( p < 0.05 \)\( \text{N}=48 \)

| Variable | Mean value | Standard deviation | A          | W_e          |
|----------|------------|--------------------|------------|--------------|
| A        | 47.80      | 21.112             | 1.000000   | -0.917829    |
| Q_e      | 12585.78   | 7238.078           | -0.917829  | 1.000000     |

Looking at the results of correlation indexes between calorific values and ash contents for experiment 1 it can be noticed that there are high values of these indexes for all products. The worst case occurred for the concentrate, but still the value is statistically significant. The same observations were found for the experiment 2. That was the basis to create regressive models, presented in Tables 3-7 and on Figures 2-6.

Table 3. Analysis of linear regression between calorific value and ash content in the feed – Experiment 1.

| Constant term | \( b^* \) | Standard error from \( b^* \) | \( b \) | Standard error from \( b \) | \( t(10) \) | \( p \) |
|---------------|----------|-------------------------------|-------|-------------------------------|-------------|------|
| \( Q_{uf} \)  | -0.929142 | 0.116917                      | -340.52 | 42.849                       | -7.94704    | 0.000000 |

where: \( b \) – value of parameter; \( b^* \) - value of parameter of normalized distribution; \( t \) – value of t-Student test; \( p \) – significance level; \( R^2 \) – coefficient of determination; \( F \) – value of F-Snedecor test.

![Figure 2](image-url)  
**Figure 2.** Regressive function for calorific value of the feed and ash content (Experiment 1, \( \text{N}=12 \))

\[
Q_{uf} = -340.52A_F + 29265.17; \; R^2 = 86.33\% \tag{1}
\]
Table 4. Analysis of linear regression between calorific value and ash content in concentrate – Experiment 1

| N=12 | b*  | Standard error from b* | b   | Standard error from b | t(10) | p     |
|------|-----|------------------------|-----|-----------------------|-------|-------|
| Constant term | 26876,63 | 1428,484 | 18,81480 | 0,000000 |
| Ac   | -0,833275 | 0,174829 | -255,87 | 53,684 | -4,76622 | 0,000761 |

Figure 3. Regressive function for calorific value of the concentrate and ash content (Experiment 1, N=12)

\[ Q_{uc} = -255,87A_c + 26876,63; \quad R^2=69,43\% \] (2)

Table 5. Analysis of linear regression between calorific value and ash content in middlings – Experiment 1

| N=12 | b*  | Standard error from b* | b   | Standard error from b | t(10) | p     |
|------|-----|------------------------|-----|-----------------------|-------|-------|
| Constant term | 29263,37 | 1806,529 | 16,19867 | 0,000000 |
| Am   | -0,945973 | 0,102536 | -342,66 | 37,142 | -9,22580 | 0,000003 |
Figure 4. Regressive function for calorific value of the middlings and ash content (Experiment 1, N=12)

\[ Q_{uM} = -342.66A_M + 29263.37; R^2=89.49\% \]  \hspace{2cm} (3)

| N=12 | 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 |

Table 6. Analysis of linear regression between calorific value and ash content in tailings – Experiment 1

Summary of regression of dependent variable: \( Q_{uT} \) R= .98843110 R²= .97699604 Adjusted R²=.97469564 F(1,10)=424.71 p<.00000 Standard error of estimation: 259.04
Figure 5. Regressive function for calorific value of the tailings and ash content (Experiment 1, N=12)

\[ Q_{uT} = -319.00 A_T + 27839.13; \quad R^2 = 97.70\% \] (4)

Table 7. Analysis of linear regression between calorific value and ash content – Experiment 2

|                | N=48 | 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 |
Figure 6. Regressive function for calorific value of the feed and ash content (Experiment 2, N=48)

\[ Q_u = -314,67A + 27627,92; R^2=84,24\% \] (5)

6. Conclusions

Basing on the conducted calculations for both experiments considered in the paper it occurred that there are high correlations between calorific values and ash contents. That means that it is possible to forecast the calorific value of the coal sample knowing its ash contents. Dry coal separation method used in these experiments indicated that it can be efficient tool to divide the feed into subproducts (concentrate, middlings and tailings) and thanks to the models the appropriate tool or technique can be selected easier and more accurately. The amount of samples considered in this paper was not sufficient to claim that the results are representative for all circumstances. These samples were prepared especially for the purpose of evaluating the FGX dry separation method. In case of having more samples with more changeable conditions of the process conductance and more parameters being measured (like sulfur contents, phosphorus contents, mercury contents, different enrichment characteristic of coal) the results would be more adequate to describe the process itself. However, this method is not popular in Poland and requires more studies.

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