Technology of fine coal grains recovery from the mining waste deposits

D Kowol and P Matusiak
Institute of Mining Technology, Division of Preparation Systems, 37 Pszczyńska Street, 44-100 Gliwice, Poland
dkowol@komag.eu

Abstract. Mining waste deposits (heaps) consist mainly of the waste rock, however, they may contain significant amount of coal, which was left after the coal beneficiation process. The laboratory tests, that verified possibilities of applying the technology used in the process of gravitational separation of raw minerals for recovery of grain class 6-0 mm are presented. The concept of recovering the combustible materials from mine waste by integration of the jig beneficiation technology with autogenous suspension bed technology is discussed.

1. Introduction
Mining waste deposits, created over many years, contain mainly mining wastes from the mechanical coal processing in coal mines. They often contain large amount of useful coal grains, which in majority can be recovered after applying the appropriate technology.

In contrast to the specificity of easily separated, large-sized grain material, processed with a good result in a pulsating jig [1,2,3], the fine-grain material creates much more problems in the industrial beneficiation process of [4].

The selection of the most profitable technology for the beneficiation of fine coal material (including coal waste), requires analysis of available methods for material separation, determination of quantitative and qualitative feed material parameters and wanted beneficiation products, as well as the process tests to verify the technological assumptions and the process parameters.

Unlike raw coal beneficiation, where the share of grains of waste fractions amounts to 20-30%, beneficiation of mining waste, containing mostly heavy grains with high ash content, is much more difficult due to impact of feed quality parameters on the ash content in the concentrate.

The selection of an appropriate technology for beneficiation of fine-grain mining waste should also take into account the impact of material graining range on the efficiency of separation process, carried out in with changes in the quality parameters of the feed. In the narrow grain class, the difference in grain density determines the grain separation effectiveness. At constant conditions, the flow through the separator with a wide graining range, separation effectiveness depends on the grains size and density, the grains size may have a greater impact than their density.

In order to obtain high separation effectiveness, beneficiation of 6-0 mm mining waste should be carried out in a multistage process for the previously separated grain classes.
2. Laboratory tests

2.1. Testing methodology

Based on the analysis of state of the art in coal feed beneficiation process of grain class 6-0 mm, the developed testing methodology was aimed at verification of effectiveness of the various separation technologies of each grain class in mining wastes smaller than 6 mm [5].

Effectiveness analyses of the material separation of grain size 6-2 mm were made, on the basis of two-product jig beneficiation technology, in a single-chamber experimental pulsating jig, using periodic flow of material through the working chamber and discharging the separation products from it.

Grain size 2-1(0.5) mm material separation effectiveness analysis was carried out on the basis of:

- technology of hydraulic two-product separation at the stand of a two-chamber suspension separator under turbulent flow of rising water stream,
- technology of an autogenous suspension bed in a fluidised bed of the beneficiation chamber under conditions of laminar flow of rising water stream.

After each test, the separation products were subjected to quantitative and qualitative analyses to determine the separation effectiveness in each grain class.

Density analyses included separation of material in heavy liquids of the following densities: 1.3; 1.4; 1.5; 1.6; 1.7; 1.8 and 2.0 g/cm$^3$. The ash content was determined in each of the obtained size and density fraction, and then, based on the results of laboratory analyses, the qualitative parameters of the beneficiation products in form of $d_{50}$ separation density, probable error $E_p$ and imperfection $I$ were determined. Figure 1 schematically shows the algorithm of the conducted tests.

![Figure 1 Algorithm of the conducted tests.](image-url)
2.2. Tests of separation effectiveness for material in class 6-2 mm using the water pulsating movement

Testing the possibility of combustible substance recovery from coal wastes of the grain class 6-2 mm, using a gravitational separation process, was carried out at the laboratory jig stand, equipped with electronically controlled air pulse valves (figure 2). In pulsating jig the screen deck was equipped with a polyurethane slotted screen of 2 mm slot size.

As a result of preliminary technological tests, airflow and bottom water controlled parameters in the jig were selected and adjusted to grain size of the separated material. The obtained parameters are given in table 1.

**Table 1. Controlled parameters of experimental jig [5].**

| Parameter                                      | Value |
|-----------------------------------------------|-------|
| Frequency, min⁻¹                               | 70    |
| Single cycle time, ms                         | 860   |
| Inlet valve opening time, ms                  | 200   |
| Inter-signal interval time1, ms               | 310   |
| Outlet valve opening time, ms                 | 200   |
| Inter-signal interval time2, ms               | 150   |
| Rate of bottom water inflow, m³/h             | 3     |
| Water pulsation in a working chamber, m       | 0.03  |
| Unit load, t/h/m²                             | 3.43  |

During separation process, the material was separated into two products: "lightweight" one and "heavy" one.
The "lightweight" product - concentrate, after discharging through the working chamber overflow, along with the process water, was dewatered on sieves with a 2 mm slots and 0.5 mm holes, successively.

The "heavy" product - waste product was continuously discharged in form of a material passed through the sieve openings of the jig's working chamber and periodically through a vertical slot with an articulated flap.

Separated material was subjected to quantitative and qualitative analyses to determine the separation effectiveness in the 6-2 mm and 6-4 mm and 4-2 mm grain size fractions.

In addition, comparative analyses of the parameters of the waste product discharged from the jig's working chamber through the sieve holes and through the vertical receiving slot of the heavy product were carried out.

The results of the beneficiation process of the 6-2 mm grain class are presented in table 2.

| Parameter | Grain class, mm |
|-----------|-----------------|
|           | 6-2  | 6-4  | 4-2  |
| Separation density, $d_{50}$, g/cm$^3$ | 1.705 | 1.691 | 1.705 |
| Probable error $E_p$, g/cm$^3$ | 0.122 | 0.123 | 1.121 |
| Imperfection I | 0.173 | 0.178 | 0.171 |

Table 2. List of parameters of separation process of the grain class 6-2 mm [5].

Analysis of the separation test results for coal waste of 6-2 mm grain size class showed that for separation density $d_{50} = 1.705$ g/cm$^3$ separation efficiency indicators were as follows: the probable error $E_p = 0.122$ g/cm$^3$, and imperfection $I = 0.173$.

Tests of two-product separation process for fine coal waste – size 6-2 mm, conducted in a pulsating jig, had small share of carbon grains and middlings, enabled obtaining a concentrate with an output of 11.7%, ash content 21.7% and a calorific value of 25.5 MJ/kg.

A comparative analysis of beneficiation results for grain sizes of 6-4 mm and 4-2 mm with shares equal to 37.5% and 62.5% showed that with similar values of separation accuracy indicators, separation of 6-4 mm grains was more effective due to the larger yield of coal fractions of density <1.5 g/cm$^3$ by 1.8% in a concentrate product.

Concentrate obtained from the beneficiated material of 6-4 mm grain size had a higher quality and had an ash content of 17.73% and a calorific value of 27.02 MJ/kg, while in the concentrate from feed
material of class 4-2 mm the ash content was 23.05% and the calorific value was equal to 24.52 MJ/kg.

The smaller share of coal incorrect grains in the waste product, discharged through the screen (0.4%), in comparison to the share of these grains in the waste product discharged through the receiving slot (1.6%) indicates the possibility of intensification of the heavy product discharge process from the jig's working surface through the screen openings. This will increase the effectiveness of 4-2 mm grain separation and the quality of the concentrate product.

Figure 3 presents in a graphic form the relationship between the separation parameters and the material grain size.

![Figure 3](image)

**Figure 3.** Impact of grain size on the distribution parameters [7].

2.3. Tests of material separation effectiveness for class 2(1)-1(0.5) mm using rising water stream

In the tests of separating the 2-0.5 mm grain size feed, a hydraulic method of material beneficiation was used. The method uses the turbulent flow of rising water stream in the stream-and-suspension separator’s working chamber (figure 4).
Figure 4. Stream and suspension separator test stand [7].

Separation of the feed in the separator’s chamber into lightweight (concentrate) and heavy (waste) products was carried out using the process (top) water supplied together with the feed to the bottom of the working chamber and the bottom water flowing through the heavy product slot.

The results of the gravitational process of the fine material depended on the flowrate of the rising water stream in the separator’s working chamber as well as on the separation density.

The selection of the top water inflow rate \( Q = 0.95 \text{ m}^3/\text{h} \) and the bottom water \( Q = 0.25 \text{ m}^3/\text{h} \) allowed obtaining, in the working chamber with a cross-section area of 0.0108 m\(^2\), the average water flow velocity of 0.031 m/s. The flow velocity of the rising water stream through the heavy product slot, with a cross-section area of 0.0008 m\(^2\), was equal to 0.084 m/s.

The separation products were subjected to quantitative and qualitative analyses to determine separation effectiveness in 2-0.5 mm, 2-1 mm and 1-0.5 mm grain size classes.

The results of analyses enabled determining the separation density for the whole material in grain sizes 2-1 mm and 1-0.5 mm and determining the separation process effectiveness for the same grain size classes basing on the probable error values \( E_p \).

The results of conducted tests are presented in table 3.

During beneficiation tests of 2-0.5 mm grain class material with a significant 72.5% ash content, the concentrate with 16.3% yield and of 25% ash content was obtained, the waste product had 82.4% ash content.

The obtained separation process effectiveness in the grain size 2-0.5 mm had the probable error \( E_p \), amounted to 0.094 g/cm\(^3\) and separation density \( D_r = 1.54 \text{ g/cm}^3 \).

The results of analysis of the material distribution parameters in size and density fractions showed a significant impact of the grain size and gravimetric composition of the feed on the yield and the quality parameters of the beneficiation products.

Comparison of the separation results for the feed of the grain class 2-0.5 mm as well as in the 2-1 mm and 1-0.5 mm classes showed better beneficiation results (\( E_p = 0.069 \text{ g/cm}^3 \) with \( D_r = 1.5 \text{ g/cm}^3 \)) for the size range of 2-1 mm grains share of which in the feed was 69.5%.

The concentrate of grain size 2-1 mm had the smallest ash content (20.54%), while this parameter in the 2-0.5 mm and 1-0.5 mm grain classes was 25.0% and 29.9% respectively.
Table 3. List of beneficiation process parameters of the 2-0.5 mm grain size class [5].

| Parameter                      | Grain class, mm |
|--------------------------------|-----------------|
|                                | 2-0.5 | 2-1   | 1-0.5 |
| Separation density, \(d_{sp}\), g/cm³ | 1.537  | 1.501 | 1.671 |
| Probable error \(E_p\), g/cm³    | 0.094  | 0.069 | 0.137 |
| Imperfection I                  | 0.175  | 0.137 | 0.203 |
| Feed <1.5                       | 12.93  | 11.03 | 17.27 |
| 1.5-1.8                        | 4.28   | 3.84  | 5.22  |
| >1.8                           | 82.79  | 85.12 | 77.51 |
| Share                          | 100.00 | 69.50 | 30.50 |
| Concentrate Output <1.5        | 16.26  | 12.22 | 25.47 |
| 1.5-1.8                        | 73.02  | 81.20 | 64.09 |
| >1.8                           | 19.75  | 14.14 | 25.30 |
| Tailings Output <1.5           | 83.74  | 87.78 | 74.53 |
| 1.5-1.8                        | 1.26   | 1.26  | 1.27  |
| >1.8                           | 3.65   | 3.73  | 3.38  |
| Partition number <1.5          | 95.09  | 95.01 | 95.35 |
| 1.5-1.8                        | 8.16   | 10.03 | 5.48  |
| >1.8                           | 71.48  | 85.18 | 48.25 |

Two times smaller separation effectiveness in the grain class 1-0.5 mm (\(E_p=0.137\) g/cm³), in comparison to the results of the class 2-1 mm, with a much higher (by 0.13 g/cm³) separation density, indicates:

- dependence of the separation process in the counter-current classifier mainly on the grain settling velocity,
- the necessity to take into account the share of 1-0.5 mm grains in a 2-0.5 mm feed in forecasts of beneficiation results.

Figure 5 presents in a graphic form the relationship between separation parameters and the grain size distribution of the material.
Figure 5. Impact of grain size on the distribution parameters [7].

2.4. Tests of the material separation effectiveness in class 1 (0.5) - 0 mm using an autogenous suspension bed

The tests of the material beneficiation process in the 2-0.5 mm grain class, obtained from the coal waste were carried out in a laboratory using the suspension part of the hydraulic fluid suspension separator model (figure 3).

The analysis used the method of suspension beneficiation of the material using an autogenous fluidised bed, obtained in a result of action of the rising water stream on the material in the upper part of the beneficiation chamber.

Separation of the material in the suspension chamber of the separator into lightweight (concentrate) and heavy (waste) products was carried out using the stream of water supplied by the flat diffusion plate, which is at the same time was the settling bottom of the working chamber.

The results of the gravitational separation process of the fine material depended on flow velocity of the rising water stream in the working chamber and the material density as well as on the parameters of the separation layer in the autogenous suspension bed and the height of its position in the chamber.

In a result of selection of the inflow intensity of the bottom water, which amounted to $Q \approx 4.5 \text{ m}^3/\text{h}$, in the working chamber with the area of 0.075 m$^2$, the flow velocity of the rising water stream was equal to 0.017 m/s.

The material of the gravitational beneficiation products was subjected to the same analyses as in the case of tests using the rising water stream.

The results of the conducted tests are presented in table 4.

During beneficitation tests of 2-0.5 mm material with a significant 71.81% ash content, a concentrate product with 12.8% yield and 16.92% ash content and a waste product with 80.68% ash content were obtained.

In comparison to the test results using a counter-current classifier, separation of the material using an autogenous suspension bed and separation density lower by 0.1 g/cm$^3$, higher quality concentrate with ash content lower by 8.1% was obtained.

The effectiveness of beneficiation process in the 2-0.5 mm grain class was characterized by the probable error $E_p$, was equal to 0.075 g/cm$^3$ and imperfection I was equal to 0.1171.
Table 4. List of beneficiation process parameters of the 2-0.5 mm grain class [5].

| Parameter          | Grain class, mm |
|--------------------|-----------------|
|                    | 2-0.5           | 2-1            | 1-0.5          |
| Separation density, $d_{50}$, g/cm$^3$ | 1.441           | 1.392           | 1.505          |
| Probable error $E_p$, g/cm$^3$         | 0.075           | 0.042           | 0.079          |
| Imperfection I     | 0.171           | 0.107           | 0.155          |
| Feed:              |                 |                 |                |
| $<1.5$             | 13.75           | 11.03           | 17.27          |
| 1.5-1.8            | 4.45            | 3.86            | 5.22           |
| $>1.8$             | 81.80           | 85.12           | 77.51          |
| Share              | 100.00          | 56.30           | 43.70          |
| Concentrate:       |                 |                 |                |
| $<1.5$             | 86.29           | 99.03           | 79.69          |
| 1.5-1.8            | 3.77            | 0.97            | 5.24           |
| $>1.8$             | 9.94            | 0.00            | 15.07          |
| Tailings:          |                 |                 |                |
| Output             | 87.16           | 92.11           | 80.78          |
| $<1.5$             | 3.06            | 3.49            | 2.42           |
| 1.5-1.8            | 4.55            | 4.10            | 5.21           |
| $>1.8$             | 92.39           | 92.41           | 92.37          |
| Partition number   |                 |                 |                |
| $<1.5$             | 19.40           | 29.14           | 11.32          |
| 1.5-1.8            | 89.12           | 98.01           | 80.69          |
| $>1.8$             | 98.44           | 100.00          | 96.26          |

Analysis of the separation results for the fed material of grain class 2-0.5 mm as well as of grain classes 2-1 mm and 1-0.5 mm showed that the highest beneficiation efficiency ($E_p=0.04$ g/cm$^3$ at $D_i = 1.39$ g/cm$^3$) was obtained for the class 2-1 mm, share of which in the feed was 56.3%.

The concentrate of grain class of 2-1 mm had the smallest, 8.34% ash content, while the value of this parameter in the 2-0.5 mm and 1-0.5 mm grain classes was 16.92% and 21.37, respectively.

In comparison to the results of 2-1 mm class separation, the efficiency of separating the grain class 1÷0.5 mm ($E_p = 0.079$ g/cm$^3$) was two times lower, and the separation density was higher by 0.11 g/cm$^3$. The difference in density of material separation was significantly lower (more favourable) than the one obtained in the counter-current classifier tests, where it reached 0.17 g/cm$^3$.

The above difference in the separation density of the size and density-fraction in the suspension separator indicates for:
- dependence of the material separation process on both, the grain settling velocity and the density of the autogenous suspension bed,
- the necessity to take into account the share of 2-1 mm and 1-0.5 mm grain classes and the differences in their separation parameters, while forecasting the beneficiation results of feed 2-0.5 mm.

Figure 6 in the graphic form presents the relationship between the separation parameters and the grain size of the material.
Figure 6. Impact of grain size on the separation parameters [7].

Figure 7 presents a comparison of the separation effectiveness for class 2-0.5 mm obtained by the hydraulic method using the rising water stream and by the method using an autogenous suspension bed.

Figure 7. Comparison of separation effectiveness of 2-0.5 mm grain class by hydraulic (1) and suspension (2) methods on the example of probable error [7].

3. The concept of beneficiation technologies for fine coal feed
Basing on the results of laboratory tests, a concept for the recovery of combustible material from coal waste was developed, integrating the technology of sedimentary beneficiation with technology using an autogenous suspension bed [5].

In order to obtain high separation effectiveness, the beneficiation of 6-0 mm coal waste will be carried out in a multi-stage manner, separately for the previously classified grain classes.
Grain class 6-2 mm
Material of grain class higher than 6-2 mm can be alternatively beneficiated in a one-compartment pulsating jig together with a 30-6 mm grain class (pulsating classifier) or after broadening the grain size range to 8-2 mm in a pulsating jig with an internal slot for heavy product discharge and the system for removing the sludge from the lower densifying box.

In comparison to the beneficiation results of the 30-2 mm grain class in a single device, the above solution, consisting in beneficiation of coal waste in 30-8 mm and 8-2 mm grain classes in separate jigs (classifiers), will ensure greater separation effectiveness due to a smaller difference between the largest and smallest grains.

Grain class 2-0 mm
For the beneficiation of the material in the 2-0 mm grain class, it is planned to use a device based on the flow of the rising water stream in the working chamber enabling the separation of grains according to their density, using an autogenous suspension bed as well as one and two-stage separation process.

In the case of beneficiation of coal waste product, which share of heavy fractions may exceed 80%, the two-stage material separation process in the 2-0 mm grain class allows obtaining a concentrate product with lower ash content, compared to one-stage beneficiation, with the same separation density.

The density separation in the narrow grain classes will be more efficient and allows to obtain a concentrate product with a lower ash content compared to the material separation with a larger grain class range.

Separation of 2-0 mm waste grains from the feed of grain class 2-1 mm, during the first material separation stage, will have a positive effect on the separation effectiveness of the second stage in a separate working chamber or in another beneficiation unit due to uniformity of density of the layers forming the autogenous bed.

As the grain size of the heavy grains increases in the feed, the size range of the grains which can be effectively separated in the suspension bed will reduce. This is due to the need to increase the rising water velocity to maintain the homogeneity of the bed layers.

Separation in one, single-chamber separator, with an autogenous suspension bed is an alternative method for the 2-0 mm grain class material beneficiation. With the application of the above technology, the significance and impact of the process of dewatering and classification of the concentrate product on its quality will increase. Separation of the smallest grains from the concentrate product, with the highest ash content, and then directing them for beneficiation in a hydro-cyclone may be a beneficial solution allowing to obtain a sufficiently low ash content in the final product concentrates.

4. Conclusions
Mine waste deposits often contain significant amount of coal grains, which can be recovered after using proper beneficiation technology.

The beneficiation of mine waste containing significant, often exceeding 90% of waste fraction grains is characterized by a considerable difficulty in obtaining a stable quality concentrate product during the material separation process.

The above problem appears especially in the case of fine material beneficiation.

Basing on the analysis of the solutions using the technologies for the separation of fine grain feed according to grain density the assumptions for testing methodology in which the grain size range of beneficiated material using different technologies was determined, were elaborated.

The results of laboratory tests were the basis for the development of recovery technologies for the 6-0 mm class fine coal grains recovered from the mine heaps, in which the integration of the jig separation technology with the technology using an autogenous suspension bed was suggested.
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