minerals

Article

Application of Jigging Beneficiation for Processing of Waste from Post-Mining Heaps for Circular Economy Purposes

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Abstract

The article presents the results of research and development work conducted as part of the H2GEO project, aimed at creating a comprehensive technology for the processing of post-mining coal waste heaps. The core of the solution is a mobile density separation system based on a pulsating jig, enabling effective recovery of carbonaceous and mineral fractions. Laboratory experiments assessed the impact of key process parameters—such as sieve slot size, pulsation frequency, and enrichment time—on the efficiency and accuracy of separation for different grain size classes. The most favorable results were obtained using a 2.5 mm screen, a pulsation frequency of 60 min^{-1}, and extended enrichment time, which ensured high-quality separation and low ash content in the carbon-bearing product. The findings supported the design of a new industrial separator (jig) equipped with advanced control systems, facilitating the production of homogeneous fractions suitable for further processing into hydrogen, geopolymers, and construction materials. The proposed solution aligns with circular economy principles, promoting waste reuse, environmental hazard mitigation, and the revitalization of degraded post-industrial areas.

Keywords: coal mine waste; processing; pulsating jig; separation; circular economy

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1. Introduction

Waste is generated in all areas of human activity, particularly in the industrial sector. One of the most environmentally burdensome industries in this respect is hard coal mining, which produces significant amounts of waste. The extracted material, before being transformed into a commercial product, is brought to the surface, where it undergoes mechanical processing aimed at separating coal from gangue rock [1,2].

Since 2007, global production of coal mine waste has been estimated at around 315 million tons annually for underground mining, which accounts for approximately 25% of the total volume of industrial solid waste [3].

Waste continues to be generated in significant amounts as part of ongoing mining activities, and its composition can vary greatly depending on prevailing geological conditions. It is estimated that the production of 1 ton of hard coal results in the generation of 0.4 tons of mining "waste material" [4].

Mining waste landfills can be found in all countries where hard coal mining has been carried out. For example, based on available and accepted data [4–6], it is estimated that the Polish coal industry produced at least 17 million tons of waste in 2024. Different sources report varying figures for the number of storage sites, the volume of stored waste, and the area occupied. Most of this waste is stored at 220 main dumps, which contain over 760 million tons of waste and cover an area of 4000 hectares [7,8]. Meanwhile, a 2019 report by the Supreme Audit Office (NIK) stated that there were 153 coal mining waste storage sites in the country, occupying an area of over 11,000 hectares [9]. After two centuries of exploitation in the Czech part of the Upper Silesian Coal Basin (Ostrava-Karviná region), there are around 300 such sites (approximately 46 waste dumps and 281 reservoirs) [10]. It is estimated—though precise data remain uncertain—that China has over 3000 gangue dumps occupying a total area of at least 20,000 hectares. According to available estimates, these may contain over 5.5 billion tons of waste [8,11].

Mining waste storage sites contribute to environmental degradation and pose numerous hazards in the form of fires, which are often associated with the release of gases that pollute the atmosphere, as well as contamination of surface and groundwater [12–14].

The most significant adverse effects of waste dump fires include:

- The presence of hot zones at the surface or shallow depths;
- The emission of harmful gases (e.g., CO, CO_2);
- Exceedances of groundwater acidity levels and concentrations of pollutants (chlorides and sulfates) in surface waters;
- Ground movements due to material loss from combustion or excavation activities;
- The formation of new pollutants that may be leached, washed away, or dispersed as dust [1,15,16].

The self-ignition process is complex and depends on various factors, such as the content of combustible substances and pyrite, oxygen availability, heat accumulation, and atmospheric conditions influencing the course of the reaction [15,17].

Especially important, in terms of the threat of environmental pollution, is the presence of geochemically unstable sulfides (mainly FeS_2—pyrite, marcasite) in the waste, which leads to the formation of acid rock drainage (ARD) and severe degradation of groundwater. Leachates from mining waste with neutral or alkaline pH (NRD—Neutral Rock Drainage) can also have significant pollution potential, e.g., due to high salinity [18]. The impact of intense rainfall and water erosion on the self-ignition of waste dumps is also being considered [19].

The scale of potential hazards posed by mining waste dumps, combined with the requirements of implementing a circular economy, compels research, development, and advancement of technologies for reusing waste to ensure efficiency and minimize environmental impact. Such activities also help reduce the land area occupied by dumps and support the reclamation and potential redevelopment of degraded sites.

Nowadays, through various processing methods, gangue rock is gaining new applications as a raw material for traditional and innovative building materials. The use of coal gangue includes cement production as well as modern products. Furthermore, gangue is used as an alternative aggregate in the construction of embankments, roads, pavements and foundations, and in the extraction of pyrites or zeolite production [20]. Due to their properties, some waste materials, e.g., those with high aluminosilicate content, can be effectively used in construction [21–23], including, for example, in the production of building ceramics [24–26].

One component of coal waste—self-burned shale—due to its chemical and mineral composition, is similar to brick clay. Its physical properties also resemble those of clay used in brick production, making it potentially suitable for ceramic manufacturing [27]. Another direction for waste utilization is its use as high-grade railway subgrade filler and for the preparation of concrete for roadbed drainage [28]. A review of the literature has shown that one of the potential products of coal waste processing may also be a pyrite concentrate [29].

In [30], the results of studies on the potential use of solid coal waste, including waste from coal washing, for the reclamation of saline and alkaline soils are presented. The results showed an increase in organic matter content, a reduction in water-soluble salts, and a decrease in soil pH. Compared to the original soil, the content of heavy metals in the reclaimed soil decreased, indicating the effectiveness of the applied technology and its compliance with environmental requirements. In turn, the results presented in [31] demonstrated that coal waste can be used as a substitute for traditional sand as fine aggregate in the production of concrete paving blocks.

The literature review revealed that activities in the area of mining waste landfill processing aimed at recovering valuable raw materials are not conducted in a comprehensive manner, that is, with the objective of maximizing the recovery of all deposited material fractions, both mineral and carbon-bearing.

Comprehensive Processing of Coal Mine Waste Heaps

In 2023, work commenced on the project "New technology for hydrogen and geopolymer composites production from post-mining waste" (H2GEO), co-financed by the Research Fund for Coal and Steel (RFCS), with the main goal of developing a comprehensive technology for the processing of coal mining waste heaps. The project is based on implementing solutions that enable the management of historical mining waste resources, promoting waste recycling and identifying new market opportunities.

A key component of the project is the development of a new technology for processing the mineral fraction and fly ash using CO_2 to produce geopolymer composites. The versatility of this technology will allow its application in other EU countries where post-mining waste heaps pose both environmental and social challenges. An equally important aspect of the project is the development of a management strategy for the energy fractions separated from the waste. Research is being conducted to develop an effective method of hydrogen production from synthesis gas obtained in the gasification of carbon-containing fractions [32].

Based on laboratory test results of the physicochemical and mechanical properties of the recovered fractions, additional potential applications for post-mining waste are being explored. Potential directions for utilization include construction, road engineering, environmental protection, mining, agriculture, and land reclamation.

To ensure high-quality raw material from mining waste for further processing, an advanced mobile separation system has been developed, with a pulsating jig as its central component. This unit will be equipped with an innovative control system enabling efficient material separation and the production of high-quality products.

The project will include assessments of the economic, environmental, social, and legal aspects of the developed waste heap processing technology, with particular emphasis on the production of geopolymer composites and hydrogen from mining waste. The results of the analyses will serve as the basis for assessing the economic viability of the processes, their environmental impact (including emissions, post-process residues, and product stability), compliance with current legal regulations, and the potential social implications of implementing the technology. Without this data, a reliable evaluation of the risks, benefits, and feasibility of the proposed solutions would not be possible. Therefore, carrying out these analyses is an essential and critically important part of the project and a prerequisite for its scientific credibility.

The comprehensive waste processing technology developed within the project will enable the gradual elimination of existing waste heaps while maximizing the environmentally friendly and economically justified use of the stored materials. This concept aligns with the vision of a circular economy, where waste generated during production can be recycled and thus become new raw materials.

2. Materials and Methods

One of the methods for separating mineral raw materials, including mining waste, is a process that utilizes differences in the densities of individual material grains. In industrial conditions, density-based separation is carried out using various devices, selected based on factors such as the particle size distribution of the feed material. The beneficiation process can be conducted using so-called heavy liquids or in a water-based medium. One commonly used device in which material separation occurs in a water medium is the pulsating jig [33–38]. Pulsating jigs represent an environmentally friendly alternative for processing mineral raw materials, as they do not require the use of heavy liquids with magnetite, which can pose environmental contamination risks. Although their separation efficiency is slightly lower compared to methods using heavy liquids, this technology can be economically competitive due to simpler operation and lower maintenance costs.

Due to KOMAG Institute's extensive experience in designing and implementing pulsating jigs, including pulsating classifiers used for the separation of mining waste [36,39,40], it was decided to apply jigging technology in a new device dedicated to the separation of mining waste and the recovery of products for further processing.

The conducted tests aimed to determine the influence of selected factors in the jigging beneficiation operation on the accuracy of separation and to identify input data for designing a new device for the industrial separation of mining waste in a pulsating water medium. The applied solutions are intended to provide flexibility in selecting operating parameters for producing products with a desired density composition, including a specific content of combustible fraction grains, and to improve the operational reliability of the industrial equipment. Therefore, the aim of the research was not to achieve the most favorable results for product parameters and separation accuracy indicators, but rather to compare the impact of parameters in the context of their selection for an industrial solution.

2.1. Laboratory Stand

The tests were conducted on a laboratory pulsating jig stand constructed at ITG KOMAG, Gliwice, Poland (Figure 1), consisting of:

- A laboratory jig model;
- A working (pulsating) air blower;
- A control air compressor;
- An electronic control system.

The laboratory jig is a model constructed from a single, dual-chamber working compartment with a working area of 0.175 m^2. At the inlet of the jig, there is a two-part feed tank with a capacity of 0.06 m^3. The device is equipped with two pairs of inlet and outlet valves that separately supply the two pulsation chambers located beneath the sieve deck. The range of volume of the working chamber is 0.007–0.046 m^3.

The stand is equipped with a modern control system, whose algorithms enable advanced control of water pulsation and product discharge, process monitoring, and the recording and processing of collected data.

Figure 1. Laboratory jig stand [41,42].

2.2. Laboratory Research

The tests were carried out using material taken from a selected mine waste heap located in Poland—Panewnicka Waste Heap. The waste used as the research material originated from the mechanical processing of coal in density separators, primarily in jigs. Twenty-four laboratory tests were carried out using three materials with different grain size ranges.

Based on analyses of the raw material (feed), it was determined that the level of filling the working chamber with material would be a rectangular prism with a base of the working sieve (0.7 × 0.25 m) and a height of 0.2 m (volume 0.0035 m^3). For each of the analyzed grain size classes, an individual separation boundary for the concentrate product was selected, resulting in the determination of layer thicknesses (product). These thicknesses corresponded to the shares of combustible fractions in the respective feeds and were larger for materials with a higher share of this fraction. The upper layer thicknesses (concentrate) for each grain size class were as follows:

- Grain size class 10–30 mm–4 cm (representing 20% of the total thickness of the layer);
- Grain size class 3–10 mm–7 cm (representing 35% of the total thickness of the layer);
- Grain size class 3–30 mm–5.5 cm (representing 27.5% of the total thickness of the layer).

The average ash contents of the above grain size classes were 76.4%, 68.2%, and 73.2%, respectively. Table 1 presents the density–ash composition of the experimental feed.

Table 1. Density–ash composition of the experimental feed [43].

Density Fraction	Feed 10–30 mm		Feed 3–10 mm		Feed 3–30 mm	
	Share	Ash Content, A [a]	Share	Ash Content, A [a]	Share	Ash Content, A [a]
g/cm^3	%	%	%	%	%	%
<1.5	5.7	8.5	12.9	9.9	9.9	9.6
1.5–1.8	5.3	38.4	6.2	38.5	5.5	38.0
>1.8	89.0	83.0	80.9	79.7	84.6	82.9
Sum	100.0		100.0		100.0	
Average		76.4		68.2		73.2

A [a]—ash content on an analytical basis.

Table 2, in turn, presents the particle size composition of the feed.

Table 2. Particle size distribution of the experimental feed [43].

Grain Class	Feed 10–30 mm	Feed 3–10 mm	Feed 3–30 mm
mm	%	%	%
20–30	42.7	0.0	19.5
16–20	17.6	0.0	8.1
10–16	39.7	0.0	21.3
6–10	0.0	63.7	31.9
3–6	0.0	36.3	19.2
Sum	100.0	100.0	100.0

In the experiments, the variables were the mesh size of the working sieve, enrichment time, and pulsation frequency.

The parameters that were analyzed were as follows:

- The size of the working sieve opening: s = 1.5 mm and s = 2.5 mm;
- Gravitational enrichment time: t = 30 s and t = 60 s, which corresponded to the unit load of 33 $t/h/m^2$ and 16.5 $t/h/m^2$, respectively;
- Pulsation cycle frequency: f = 40 min^{-1}, f = 60 min^{-1} and f = 80 min^{-1};
- Process water supply flow rate: Q = 4.5 m^3/h.

The selection of the screen slot size was based on several factors. KOMAG Institute's experience indicated that it was sufficient for effective loosening of the material. Moreover, the maximum slot size used in the experiments (s = 2.5 mm) ensured more stable experimental conditions by minimizing grain loss through the screens.

A total of 24 individual tests were carried out. The mass of the material in a single sample was approximately 48 kg, so in total, over 1100 kg of mining waste was processed during the conducted studies.

Table 3 presents all the parameters of the experiments.

Table 4 summarizes the pulsation parameters in the form of inlet and outlet times of the pulsation disk valves in the individual experiments. These times were directly dependent on the pulsation frequency. A sinusoidal pulsation cycle was used in all experiments.

Table 3. Settings of the laboratory jig stand for individual trials [43].

A	B	C	D	E	A	B	C	D	E
1	10–30	1.5	40	60	13	10–30	1.5	80	60
2	3–10	1.5	40	60	14	3–10	1.5	80	60
3	3–30	1.5	40	60	15	3–30	1.5	80	60
4	10–30	1.5	40	30	16	10–30	2.5	40	60
5	3–10	1.5	40	30	17	3–10	2.5	40	60
6	3–30	1.5	40	30	18	3–30	2.5	40	60
7	10–30	1.5	60	60	19	10–30	2.5	60	60
8	3–10	1.5	60	60	20	3–10	2.5	60	60
9	3–30	1.5	60	60	21	3–30	2.5	60	60
10	10–30	1.5	60	30	22	10–30	2.5	60	30
11	3–10	1.5	60	30	23	3–10	2.5	60	30
12	3–30	1.5	60	30	24	3–30	2.5	60	30

A—Test number, B—Grain class, mm, C—The size of the working sieve opening, mm, D—Pulsation frequency, min^{-1}, E—Enrichment time, s.

Table 4. The duration of the pulsation cycle phase [43].

Duration of the Pulsation Cycle Phase, ms	Pulsation Frequency, min^{-1}		
	40	60	80
Inlet	345	230	173
Interval	375	250	188
Outlet	345	230	173
Interval	435	290	216

3. Results

The obtained separation products (carbon-bearing and mineral) were subjected to the planned analyses and determinations:

- Density analysis in heavy liquids (based on zinc chloride) with densities of 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8 g/cm^3 according to PN-G-04559:1997 [44];
- Determination of ash content in the obtained density fractions (<1.3; 1.3–1.4; 1.4–1.5; 1.5–1.6; 1.6–1.7; 1.7–1.8, and >1.8 g/cm^3) according to PN-ISO 1171:2002 [45].

The results of the density analyses served as the basis for determining the fundamental separation accuracy indicators, such as probable error and imperfection, which were determined according to PN-G-07020:1997 [46].

3.1. Quantitative and Qualitative Parameters of Separation Products

3.1.1. Grain Class 10–30 mm

The most favorable results in terms of the quality of separation products were obtained during experiment no. 19, which was conducted using a pulsation frequency of 60 min^{-1}, a longer enrichment time, and a larger slot in the screen deck (s = 2.5 mm). For these parameters, the lowest ash content in the carbon-bearing product and the highest in the mineral product were achieved. Very similar results were obtained in other experiments conducted with a longer enrichment time corresponding to a lower load on the device, both for a frequency of 40 min^{-1} (s = 1.5 mm, s = 2.5 mm) and f = 60 min^{-1} for s = 1.5 mm. Significantly worse results were obtained for shorter enrichment times.

3.1.2. Grain Class 3–10 mm

The best qualitative results were obtained during the experiments in which a slot size of s = 2.5 mm was used, with frequencies of 40 min^{-1} and 60 min^{-1}. Slightly worse quality parameters, for the same frequencies, were achieved in experiments where the jig unit was equipped with a screen deck with a slot size of s = 1.5 mm. Acceptable results, compared to the others, were obtained using a frequency of 80 min^{-1}. At the same time, for these tests, the highest calorific value of the carbon-bearing product and the lowest for the mineral product were obtained.

3.1.3. Grain Class 3–30 mm

The enrichment test results for the 3–30 mm grain size class confirmed the relationships observed during the separation tests of other grain size classes. Once again, the most favorable results were obtained with a frequency of 60 min^{-1} and a slot size of s = 2.5 mm. Slightly worse results were achieved with a frequency of 40 min^{-1}. For these parameters, the highest quality carbon-bearing and mineral products with minimized combustible content were obtained. As with other grain size classes, shortening the enrichment time had a very negative impact on product parameters.

The results obtained from the tested materials are summarized in Table 5.

Table 5. Summary of selected laboratory test results [43].

Test Number	Carbon-Bearing Product		Mineral Product	
	Product Mass Yield %	Average Ash Content, A^a %	Product Mass Yield %	Average Ash Content, A^a %
		Grain class 10–30 mm		
1	20.39	49.07	79.61	83.38
4	20.22	55.26	79.78	81.67
7	20.19	49.55	79.81	83.26
10	20.31	56.52	79.69	81.28
13	20.05	52.12	79.95	82.27
16	20.30	49.11	79.70	83.44
19	20.18	48.50	79.82	83.47
22	20.54	55.22	79.46	82.06
		Grain class 3–10 mm		
2	29.36	40.63	70.64	79.81
5	29.54	46.96	70.46	76.56
8	29.31	40.66	70.69	79.93
11	29.69	46.53	70.31	76.69
14	29.53	42.87	70.47	78.50
17	29.45	40.57	70.55	79.83
20	29.54	40.38	70.46	80.07
23	29.19	46.09	70.81	76.55
		Grain class 3–30 mm		
3	27.39	44.80	72.61	84.12
6	27.76	50.17	72.24	81.79
9	27.68	44.38	72.32	84.14
12	27.73	48.85	72.27	82.28
15	27.62	46.25	72.38	83.35
18	27.43	44.40	72.57	84.15
21	27.58	43.67	72.42	84.26
24	27.60	47.86	72.40	82.34

A^a—ash content on an analytical basis.

3.2. Separation Accuracy Parameters

The results of the density separation of jigging beneficiation products enabled the calculation of indicators characteristic of the beneficiation process accuracy (Supplementary Materials)

Based on the shares of individual density fractions, separation numbers were determined, and separation curves for individual feeds were prepared according to the specified experimental parameters. For each analyzed grain size class, based on the shares of individual density fractions in the feed and products, separation numbers were calculated, and then separation indicators were determined from the separation curves approximated by a 3rd-degree polynomial. The calculated indicators are summarized in Table 6.

Table 6. Separation accuracy parameters [43].

Parameter	Test number							
Grain Class 10–30 mm								
Parameter	1	4	7	10	13	16	19	22
Separation Density D_{50}, g/cm^3	2.130	1.975	2.070	2.040	2.080	2.115	2.145	1.970
Probable Error E_p, g/cm^3	0.245	0.498	0.273	0.535	0.365	0.258	0.235	0.453
Imperfection, I	0.217	0.510	0.255	0.514	0.338	0.231	0.205	0.466
Grain Class 3–10 mm								
Parameter	2	5	8	11	14	17	20	23
Separation Density D_{50}, g/cm^3	2.180	2.025	2.150	2.075	2.020	2.205	2.220	1.910
Probable Error E_p, g/cm^3	0.255	0.515	0.273	0.510	0.340	0.215	0.195	0.493
Imperfection, I	0.216	0.502	0.237	0.474	0.333	0.178	0.160	0.541
Grain Class 3–30 mm								
Parameter	3	6	9	12	15	18	21	24
Separation Density D_{50}, g/cm^3	2.190	1.990	2.210	2.060	2.125	2.210	2.220	2.140
Probable Error E_p, g/cm^3	0.193	0.300	0.173	0.305	0.258	0.173	0.160	0.268
Imperfection, I	0.162	0.303	0.143	0.288	0.229	0.143	0.131	0.235

The most favorable separation parameters for the grain size class 10–30 mm were obtained in the experiment where a pulsation frequency of 60 min^{-1} was used, along with a longer beneficiation time and a screen deck equipped with a slot screen with a slot size of 2.5 mm. For this case, the imperfection value was 0.205 and the probable error was equal to 0.235 g/cm^3.

Similarly favorable results were obtained in experiments conducted with a frequency of 40 min^{-1} on both tested screen decks (1.5 mm and 2.5 mm). For these experimental parameters, the imperfection was equal to: 0.217 and 0.231, and the probable error was 0.245 g/cm^3 and 0.258 g/cm^3.

The worst results were obtained for shorter beneficiation times (simulating increased load on the device), especially in the case of screen decks with a smaller slot size.

In the case of the grain size class 3–10 mm, distinctly the most favorable separation parameters were obtained by using a screen deck with an increased slot size (2.5 mm). The best results were achieved with a pulsation frequency of 60 min^{-1}, where the imperfection was 0.160 and the probable error was equal to 0.215 g/cm^3. A very similar separation accuracy was obtained at a frequency of 40 min^{-1}, where the above-mentioned indicators were 0.178 and 0.215 g/cm^3. Significantly (more than twice) worse results were obtained for the smaller slot size of the screen deck (1.5 mm) and shorter beneficiation times.

Similarly, in the case of enriching material with a grain size of 3–30 mm, the most favorable results in terms of separation accuracy were obtained with a larger slot size (2.5 mm) of the screen deck and longer beneficiation times (60 s). Slightly better results were achieved with a pulsation frequency of 60 min^{-1} compared to a frequency of 40^{-1}. The lowest indicators were 0.131 and 0.160 g/cm^3 in the case of test number 20. In the case of this grain size class and class 10^{-3} mm, fairly favorable separation results were also obtained for the highest of the tested frequencies, which was 80 min^{-1}.

4. Discussion

Based on the test results, a significant impact of the studied parameters on the enrichment efficiency and the quantitative and qualitative parameters of the separation products was demonstrated.

The most favorable results in terms of product quality and simultaneously the efficiency of separation for all the tested feeds were obtained at a pulsation frequency of 60 min^{-1}. Very similar and favorable separation results were achieved at a pulsation frequency of 40 min^{-1}. For grain classes with a large proportion of finer grains (<10 mm), acceptable results were obtained at a frequency of 80 min^{-1}.

The enrichment time, which corresponds to the load on the device, had a very significant impact—extending the enrichment time (that is, reducing the unit load) allowed for significantly more favorable results. The exact value of the unit load should be determined experimentally under industrial conditions, but it seems that, to maintain an acceptable efficiency in the separation of mining waste, it should not exceed 20–25 $t/h/m^2$.

The analysis of the results also showed that slightly better test results were obtained for a larger slot in the screen deck (s = 2.5 mm).

The implementation of an industrial device using the data obtained during these tests should enable significantly more favorable results and, consequently, homogeneous separation products:

- Of low density, consisting mostly of grains of the combustible fraction;
- Of high density, consisting mostly of grains of the mineral fraction.

The separation of waste into two products with different properties offers broad opportunities for their industrial use. In line with current trends, the combustible fraction can be utilized in gasification and hydrogen production technologies, as well as a feedstock for the production of low-emission fuels [47]. Such an approach is consistent with the energy transition strategy, combining the reduction in primary fuel consumption with the efficient management of coal waste.

The mineral fraction, on the other hand, depending on the physical and mechanical properties of the grains, may find wide application in many sectors of the economy—from land reclamation of degraded areas, through road aggregates, to the production of geopolymers, i.e., modern construction materials [48,49]. One of the key issues determining the use of separated waste is the content of combustible fraction grains. For example, for land reclamation purposes, it is necessary to use a fraction free of such grains. Conversely, in the case of calcination—thermal transformation of waste into metakaolin—a certain content of combustible fraction grains is even desirable, as it ensures the autothermal nature of the process [50].

Flexibility in selecting the operating parameters of industrial waste separation equipment will make it possible to produce products with desired density compositions, including the content of combustible fraction grains.

5. A New Solution for Industrial Separation of Mine Waste

Tests carried out on the laboratory jig stand allowed for the selection of input data for designing a new device for the industrial separation of mine waste.

5.1. Input Data for Design

Laboratory tests showed that both the shape and frequency of pulsation have a significant impact on the efficiency of the enrichment process. Based on these results, a disk pulsation valve was selected and designed at the KOMAG Institute for the new. It allows for easy curve shaping and frequency adjustment during operation, without physical interference, unlike rotary valves. Settings can be modified via the control panel or remotely if a wireless module is installed. The new jig will include an advanced version of this valve, with four disks and two chambers supplying air separately to the front and rear of the deck, enabling more precise pulsation control (Figure 2).

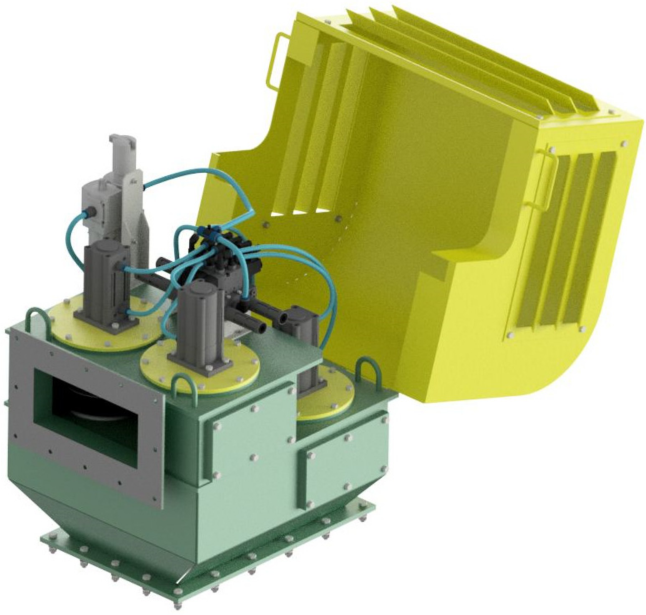

Figure 2. The ZP-4 disk pulsation valve [own work].

In the designed enrichment device, a rotary cell receiver was chosen due to its precise throughput control and minimal process water outflow—advantages unmatched by other solutions. The scraping rotor will be modified with flexible polyurethane-lined blades mounted on adjustable sliding fittings, reducing grain jamming and allowing material collection in the 3–30 mm range (with some up to 40 mm). These changes are expected to improve rotor and body durability. Additionally, a clean water sealing and flushing system will prevent material buildup and reduce wear around the rotor's seals (Figure 3).

The new pulsatory jig will feature a 2000 $\times$ 2000 mm screen deck, inclined at 5.8° (Figure 4), selected based on lab tests as optimal for 100 Mg/h throughput. It uses modular screens with a steel frame and polyurethane surface, with 2.5 mm slots—proven more effective than 1.5 mm in tests—offering better pulsation and density separation while limiting fines below the 3 mm feed size. Screens are mounted with clamping strips and wooden wedges, ensuring a secure yet easily replaceable setup under heavy-duty conditions.

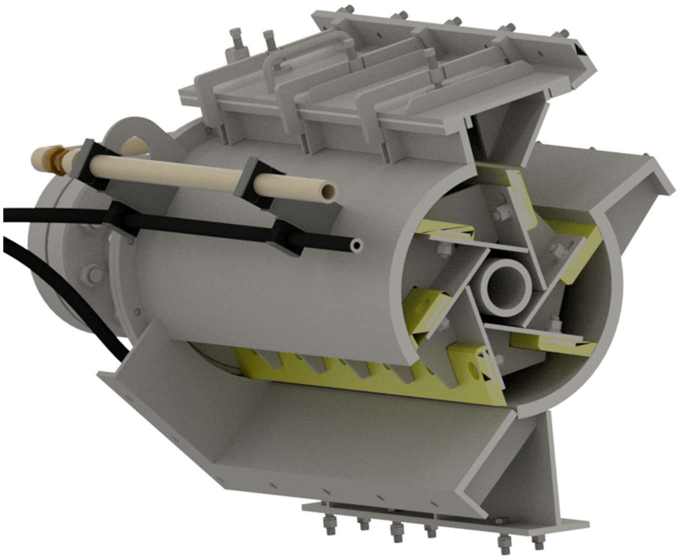

Figure 3. Mineral fraction receiver—cross-section [own work].

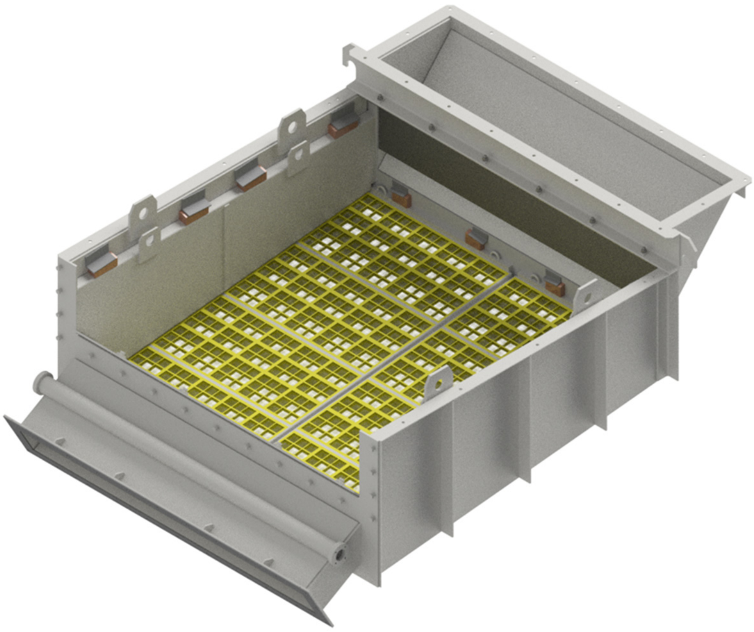

Figure 4. Working trough with polyurethane screen deck [own work].

5.2. New Pulsating Jig for Coal-Mining Waste Separation

The newly developed device—a pulsating jig—features a single working chamber measuring 2 m in length and 2 m in width, providing a total working area of 4 m^2 (Figure 5). The chamber is divided into two pulsation zones, each 1 m long, with independent supplies of operating air and bottom water.

The separator is equipped with a system of control and discharge components, including a receiver for the heavy (mineral) product, an overflow outlet for the light (coal-bearing) product, a float-based lever sensor, and elements responsible for generating pulsation and loosening the feed material within the working bed. These include a pulsation valve, a compressed air manifold, and a water system with automated dampers.

The device operates based on density-driven separation of material in a pulsating water medium. The primary outputs are: a mineral-rich product discharged via a rotary receiver, and a coal-rich product discharged over the overflow weir of the working chamber.

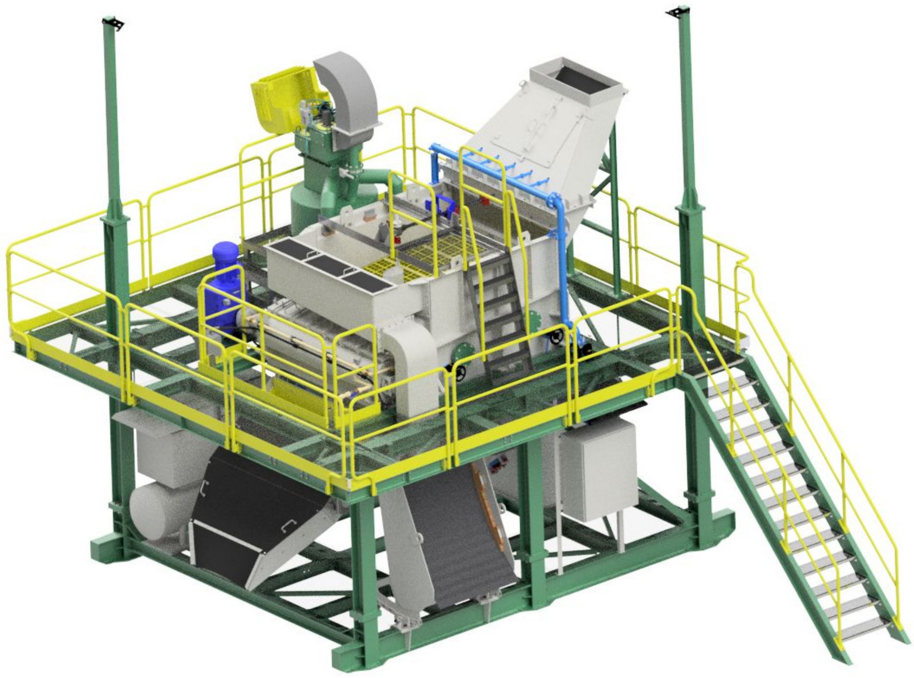

Figure 5. Prototype of the mobile system for separation of mining waste S-100, developed in the H2GEO project [own work].

An integral component of the system is the SES electronic control unit, which manages both the pulsation valve and the mineral product receiver. It enables adjustment of key process parameters, such as the pulsation cycle of the jig bed and the scraper's rotational speed, depending on the type of feed and the load conditions. This facilitates the production of high-quality, uniform separation products for further processing into high-value products such as hydrogen and geopolymers.

Table 7 presents selected new design solutions implemented in the new pulsating jig, along with their advantages compared to previous solutions. The implemented changes affect both the improvement of operational efficiency and reliability, as well as the facilitation of maintenance and adjustment tasks.

Table 7. Selected design solutions in the pulsating jig [own work].

Assebly/ Unit	Previous Design	Current Design	Advantages
Gravel receiver	"Granupack" sealing system	A labyrinth seal and a flushing system have been added.	The additional protection safeguards the receiver plates from wear by removing fine particles transported by the scraper, thereby contributing to an extended service life.
Pulsation valve	Pulsation valve supply and discharge manifold	Valve islands	The solution facilitates assembly and maintenance, while also significantly enhancing the precision of valve adjustments.

Table 7. *Cont.*

Assebly/ Unit	Previous Design	Current Design	Advantages
Working trough	Mounting of screen decks using a wedge system	Use of a longitudinal bar along the screen deck, enabling clamping of the screen deck.	The new screen deck mounting system is simpler, faster, and more durable, resulting in higher operational efficiency and reduced downtime.
Air supply manifold	Tall manifold tank, above the pulsation jig	Lowered collector tank, to the height of the pulsation jig.	Improved access to the pulsation valves, facilitating their adjustment and maintenance.
Maintenance platform	Full-width platform over the working trough	Lowered platform over half of the working trough	Improved access to the float sensor for easier adjustment and maintenance.

6. Conclusions

The development and implementation of advanced technologies for the processing of coal mine waste heaps represent a significant step toward accelerating the reclamation of degraded post-mining areas. The application of modern separation techniques and the recovery of secondary raw materials enables the restoration of ecological and economic functions in these areas, aligning with the sustainable development strategies of post-industrial regions.

Developed based on years of experience and detailed research findings, the new pulsating jig represents an innovative solution that will enable the effective separation of mining waste. As a result, it will be possible to obtain high-quality, homogeneous products, which can then be efficiently processed using advanced technologies.

Progress in innovative processing technologies makes it possible to convert separation waste into high-value products such as geopolymers, synthetic aggregates, and hydrogen. This not only increases the efficiency of resource utilization but also significantly reduces the need for primary raw material extraction. Such an approach is consistent with the principles of a circular economy, promoting the optimal use of the material potential contained in waste heaps.

Comprehensive reclamation of mining waste disposal sites will also contribute to the elimination of various environmental hazards, including dust emissions, contamination of surface and groundwater, and the risk of endogenous fires. At the same time, it will create opportunities for the redevelopment of reclaimed areas for industrial, energy-related, and social purposes, such as green spaces and recreational zones.

The implementation of these solutions may serve as a catalyst for the development of new sectors within the local economy, particularly in areas related to waste material processing, the production of innovative construction materials, and the revitalization of degraded sites. As a result, it will be possible to create new jobs, enhance the investment attractiveness of post-mining regions, and sustainably strengthen their long-term development potential.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min15111108/s1, Parameters Characterizing the Beneficiation Operation.

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