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Vibrations of the technological head of the abrasive water jet during cutting of structural steel

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Abstract:

Vibration measurement is a fundamental aspect of ensuring the optimal and reliable operation of machinery, with implications for production quality, economic efficiency, and safety. The monitoring of machine condition provides essential data for the early detection of damage to machine parts, thereby preventing unanticipated failure modes and disruptions in production. Accordingly, this paper focuses on the measurement and assessment of fundamental vibration parameters, with a particular emphasis on frequency and vibration acceleration amplitude that allows to optimize the production quality assessment. Experimental measurements were conducted on a technological head of production system using abrasive water jet technology (AWJ) with a varied feed rate while cutting two types of structural steel. Based on the results of these measurements, recommendations were formulated regarding suitable and inappropriate combinations of operating parameters, thereby enhancing current knowledge regarding the influence of technological parameters on the amplitudes of vibration acceleration in the operation of production systems with AWJ technology.

Keywords: abrasive water jet, feed rate, abrasive mass flow, vibration amplitude, frequency spectrum

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1. Introduction

The fundamental principle of water jet machining technology is the removal of material by means of a liquid, typically containing solid particles, impinging upon a workpiece in a manner that enhances the process efficiency [1]. The liquid is concentrated into a narrow jet that flows from the nozzle under sufficient pressure and impacts the material, using appropriate technological tools. As the jet interacts with the machined material, it gradually deflects in the cutting direction and loses kinetic energy. In clean water jet cutting, pure water is employed, which has undergone chemical and mechanical treatment without the addition of particles. The utilization of high-pressure liquid properties, typically about 400 MPa, serves to create an effective cutting tool [2]. The abrasive water jet, which may be considered a type of grinding tool, employs abrasive grains dispersed in the jet to enhance cutting efficiency. Its material removal mechanism is similar to that of traditional machining methods. The majority of water jet cutting machines achieve elevated pressures through the use of a multiplier, which generates high pressures based on the surface area differential between two interconnected pistons. The flexibility and cold cutting capabilities of abrasive water jets render them advantageous for cutting an array of materials, including those that are exceedingly hard or soft, composites, and sandwich materials that are challenging to machine with conventional technologies.

The cutting of materials by abrasive water jets (AWJ) has been the subject of study for several decades. The scientists who pioneered this field of research were Hashish [3] and Zeng and Kim [4]. Subsequently, further investigations were conducted with the aim of improving the machining process, for example by Kovacevic and Yong [5, 6]. The current state of research on abrasive water jet technology indicates that one of the significant challenges is the quantification and modeling of the impact of technological parameters on surface quality parameters, particularly on wear-resistant steels. The assessment of cutting quantity and quality has been a persistent area of investigation by several research groups [7–9].

Despite the emergence of an expanding array of solutions to this problem, including methodologies and evaluations of experiments that are valid for specific measurement conditions, the current solutions still lack comprehensive coverage of several variations. Microscopic models that describe the mechanism of material cutting have been developed, as have macroscopic models of cutting front behavior. The Ostrava group has also presented an interesting multi-parametric phenomenological description of the cutting process [10, 11]. The research group at TU Košice commenced their investigation into this field as part of a broader program of research into the operational states of manufacturing processes utilizing progressive technologies [12, 13]. This was followed by an examination of the impact of process parameters on surface quality.

In addition to numerous experimental studies aimed at elucidating the factors influencing the performance of the cutting process, a substantial body of research has been conducted to model the processes between the jet and cutting of the material, with the objective of gaining insight into the underlying physical mechanisms [14]. Partial analyses of input technological factors pertaining to the generation of vibration have also been conducted [15].

Despite the continuous studying of the variations of developed solutions to this problem, including methodologies and evaluations of experiments tailored to specific measurement conditions, current solutions still fail to cover several conditions. Abrasive water-jet cutting is a multiparametric process where the quality of the output characteristics is dependent on the inputs. This dependency has been substantiated through various experiments and theoretical analyses and is getting better understood. Nevertheless, there are numerous ongoing efforts to develop models that characterize the quality of the cut area under specific conditions. These models take into account a number of factors, including the material type and thickness, the feed rate and distance of the technology head, the abrasive mass flow rate and grain size, operating pressure, and other parameters [16, 17].

The present article examines the effect of the technological head feed rate and type of machined material on the technological head vibration characteristics. The evaluation is based on a graphical comparison and an analysis of the effect of changing factors on the vibration acceleration amplitude and frequency of the technological head vibrations. Furthermore, the presented experimental work aims to supplement data applicable for modelling and diagnostic processes in the multi-factorial water-jet technology.

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2. Experimental Materials and Methods

The AWJ system used at experiments comprises the following main components:

A table XY CNC WJ1020-1Z-EKO for cutting applications utilizing the abrasive water jet technology, A PTV 19/60 HSQ 5x type multiplier to generate high-pressure water at a flow rate of up to 1.9 dm^3/min (minute is used in this segment to express volume flow as well as feed rate over time), and a technological head PASER IIITM with focusing tube (Fig. 1).

In this research, the total of six experiments were conducted. All measurements started from the same initial position, designated as point X (320 mm, 370 mm), to ensure consistency and accuracy. The distance between the water jet focusing tube and the material being cut was maintained at a distance of 2 mm. The experiments were also conducted under the following additional conditions:

The machined material parameters:

- Thickness: 10 mm
- Machined steel type: 12 050; 11 523

The technological parameters:

- Water working medium pressure: 380 MPa
- Abrasive type: Australian garnet (AG)
- Abrasive average grain size: MESH 80 (0.275 mm)
- Abrasive mass flow rate: 230 g/min
- Water orifice diameter: 0.25 mm
- Focusing tube diameter: 1.02 mm
- Focusing tube length: 76 mm
- Cutting head feed rate: 40 mm/min; 100 mm/min; 400 mm/min.

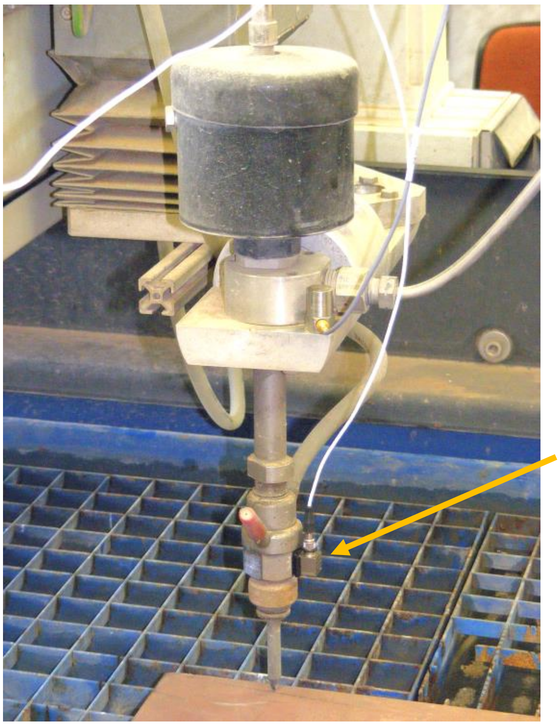

Fig. 1. Technological head with installed accelerometer marked with an arrow

The single-axis piezoelectric accelerometer Omega ACC103 was used to measure the vertical vibrations during the experiments. The basic technical parameters of the sensor are listed in Table 1.

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Table 1. Selected technical parameters of the Omega ACC103 accelerometer

Acc. range (±pk) [m.s^{-2}]	4900
Nominal voltage sensitivity (at 160 Hz) [mV/g]	10
Frequency range [Hz]	2 – 10,000
Amplitude linearity [%]	±2
Rated output shift [%]	up to ±5

Data acquisition was performed using NI-9233 hardware with the main technical parameters listed in Table 2. The LabVIEW SignalExpress software by National Instruments was used for data recording and processing.

Table 2. Selected technical parameters of the NI-9233 DAQ module

ADC resolution [bit]	24
Dynamic range [dB]	102
Max. sampling rate [Sa/s]	50 k
Time base clock frequency [Hz]	12.8 M

3. Results

The selected machined materials (steels 12 050 and 11 523) were subjected to two different feed rate speeds of the technological head (50 and 100 mm/min), and the resulting vibration acceleration amplitude was recorded in the form of time courses. An example of the time record of the vibration acceleration amplitude for both materials cut at a feed rate of 40 mm/min is depicted in Figures 2 and 3. The Fast Fourier Transformation was used to evaluate the vibration acceleration amplitude values, as recorded in the time series, over the frequency range of 100 Hz to 10 kHz, with a frequency step of 100 Hz.

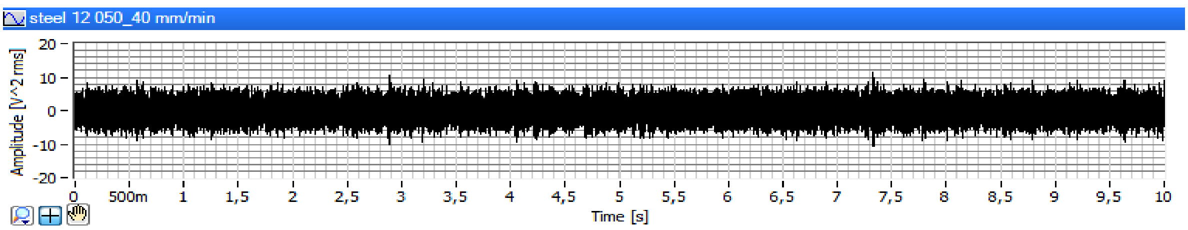

Fig. 2. A time record of the vibration acceleration amplitude of 12 050 steel cutting at a feed rate of 40 mm/min

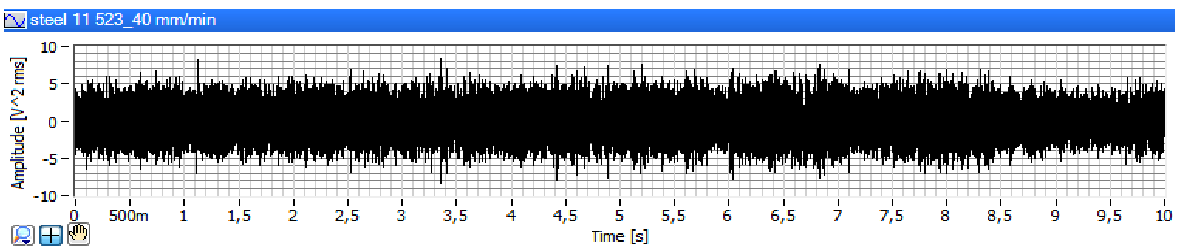

Fig. 3. A time record of the vibration acceleration amplitude of 11 523 steel cutting at a feed rate of 40 mm/min

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The evaluation of measured values involves constructing graphical representations of the dependencies between variables and the frequency range of vibration acceleration amplitude of the technological head within the frequency range of 0 to 10 kHz. For the material steel 12 050, the cutting process at a feed rate of 40 mm/min demonstrates alterations in vibration acceleration amplitude in relation to frequency, as shown in Fig. 4.

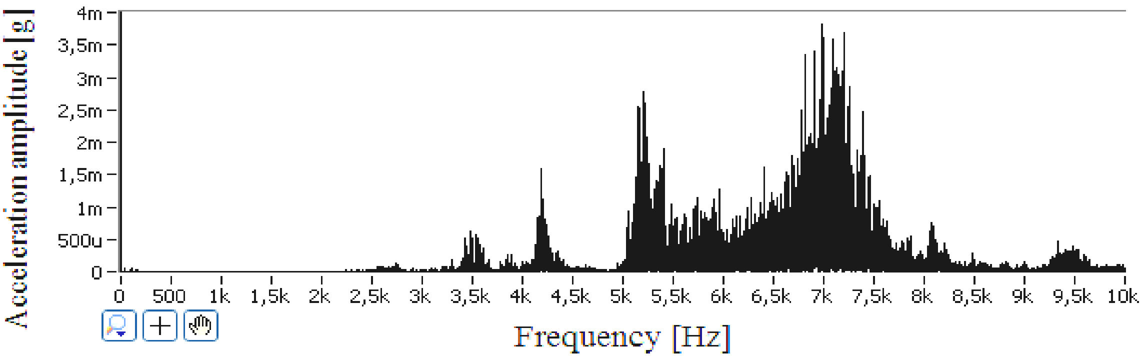

Fig. 4. An acceleration amplitude dependency on the vibration frequency of 12 050 steel during the cutting process at a feed rate of 40 mm/min

The graphical dependencies and envelopes were evaluated for feed rate speeds of 100 and 400 m/min. The graphical dependencies of acceleration amplitude and vibration frequency and frequency range envelope were analyzed for machined steel 11 523 at technological head feed rates of 40, 100, and 400 mm/min.

Figures 5 and 6 present graphs of vibration acceleration amplitude envelopes and frequency range for the two selected steel material types and the three studied feed rate speeds of 40, 100, and 400 mm/min.

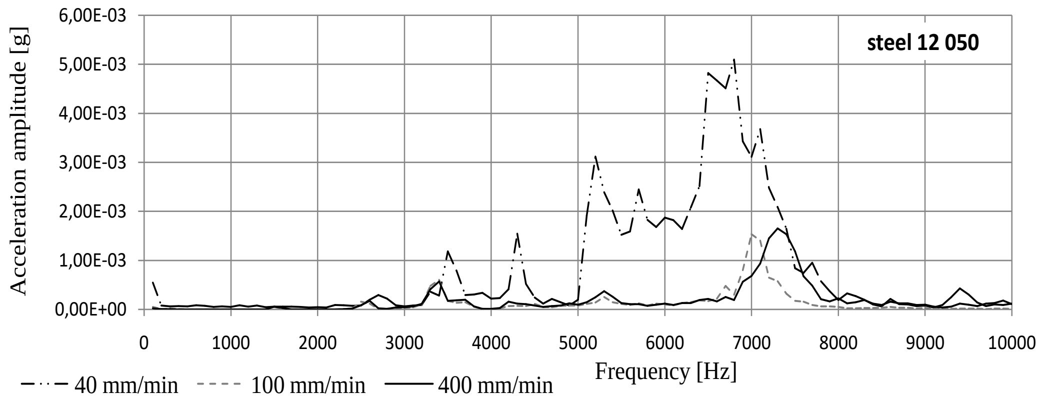

Fig. 5. The technological head vibration frequency spectrum envelopes when cutting the 12 050 steel

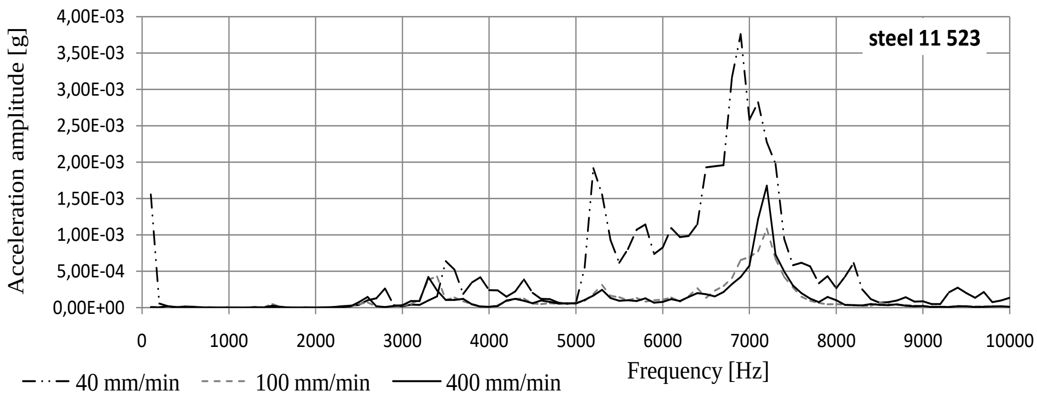

Fig. 6. The technological head vibration frequency spectrum envelopes when cutting the 11 523 steel

Figures 7-9 present graphs of vibration acceleration amplitude envelopes and frequencies for the various feed rate speeds under investigation.

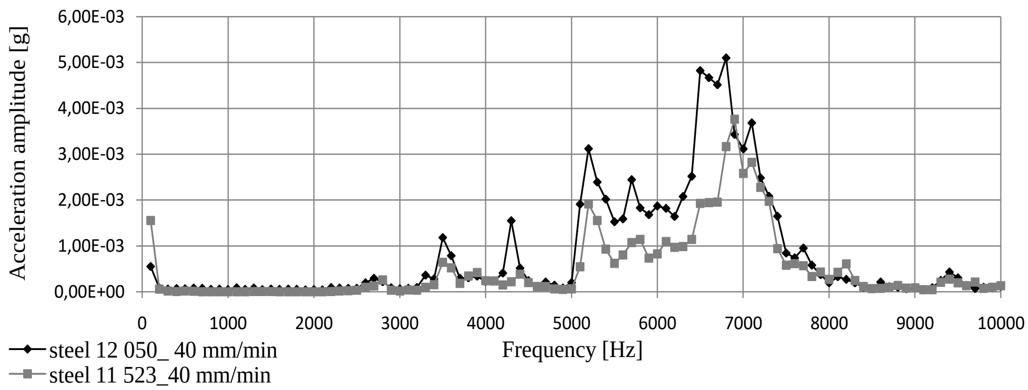

Fig. 7. The technological head vibration frequency spectrum envelopes comparison at the cutting feed rate of 40 mm/min

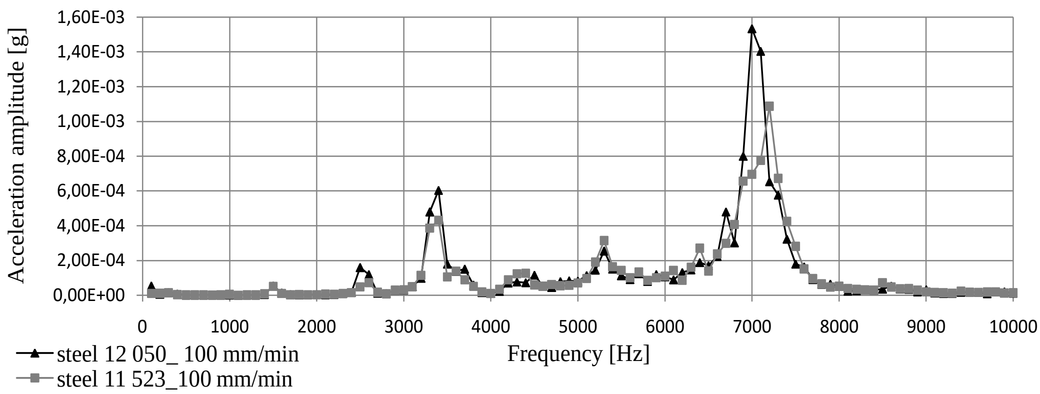

Fig. 8. The technological head vibration frequency spectrum envelopes comparison at the cutting feed rate of 100 mm/min

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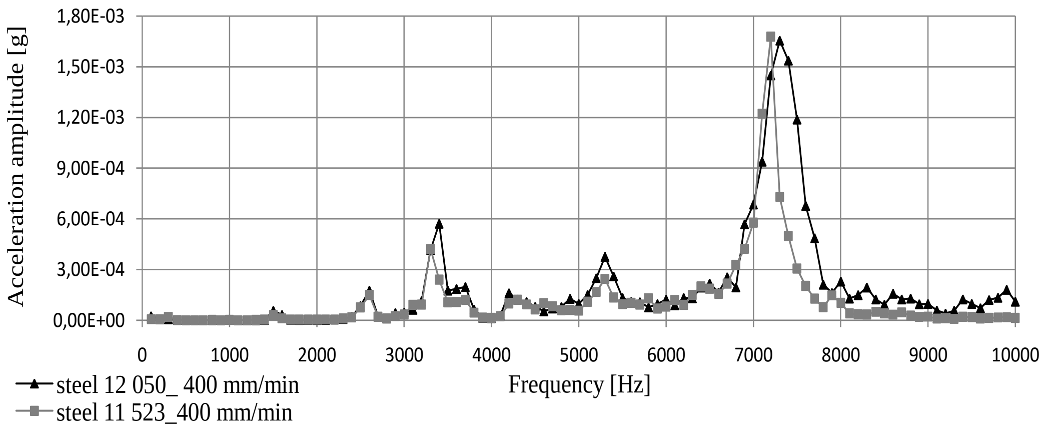

Fig. 9. The technological head vibration frequency spectrum envelopes comparison at the cutting feed rate of 400 mm/min

The maximum vibration acceleration amplitude values of the technological head are situated within the frequency range of approximately 6.8 kHz to 7.3 kHz. The following points summarize the measured values of the experimental cutting of steel materials 10 050 and 11 523 using the abrasive water jet technology, in accordance with the specified conditions.

It was observed that the highest vibration acceleration amplitude values occurred at the three measured technological head feed rates during cutting of both sample materials within the frequency range from 6.8 to 7.3 kHz, which is within the examined range of 100 Hz to 10 kHz. Furthermore, it was found that the vibration acceleration amplitude initially decreased and then increased moderately with an increase in the technological head feed rate when cutting the steel 12 050 material within the aforementioned examined range. A comparison of the feed rates 40 mm/min and 100 mm/min reveals a drop of 69.9%.

In the case of cutting steel 11 523 material in the examined range, an increase in the numerical value of the feed rate initially results in a decline in vibration acceleration amplitude, followed by a gradual and consistent growth. A comparison of the feed rates 40 mm/min and 100 mm/min reveals a drop of 71.13%.

The vibration acceleration amplitude for both materials in the aforementioned range reaches its highest value at the feed rate of 40 mm/min. The highest values of the vibration acceleration amplitude for the three measured technological head feed rates during the cutting of both sample materials are located in the frequency range from 6.8 to 7.3 kHz of the examined range from 100 Hz to 10 kHz.

The vibration acceleration amplitude firstly drops and then grows moderately with the increasing value of the technological head feed rate when cutting the steel 12 050 material in the examined range. When comparing the feed rate 40 mm/min with 100 mm/min, the drop is 69.9%.

4. Conclusion

This article presents the findings of a research study that examined the impact of different technological parameters (material type and feed rate) on the acceleration amplitude and vibration frequency of the technological head during abrasive water jet machining. With regard to the materials and feed rates under examination, the study identifies specific maximum values of vibration acceleration amplitude within the frequency range of 6.8-7.3 kHz.

Based on the graphical dependencies that were created and evaluated, the following recommendations can be formulated for steels 12 050 and 11 523. The experimental conditions indicate that it is preferable to avoid using a feed rate of 40 mm/min. Furthermore, the use of feed rates of 100 or 400 mm/min is recommended, as these speeds have been shown to generate significantly lower vibration acceleration amplitudes.

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The presented work contributes to long-term research and is in good agreement with results reported previously.

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Sustainable development, i.e. environmental, technological and economic aspects in mineral engineering

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Abstract:

The chapter presents examples of innovative approaches to developing sustainable mineral engineering. Global and Polish initiatives related to the energy transition of the mining industry are given. Completed projects related to the green branch of mineral mining are discussed. Reference was made to the issue of mining waste management. The importance of these activities in environmental, technological and economic aspect is highlighted.

Keywords: sustainability, mineral engineering, green energy, green technologies, flotation tailings

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1. Introduction

In recent years, a significant change in the dynamics of growth in global mineral mining has been observed. For example, in the 2000s, total global mineral mining amounted to about 60 billion tons, currently it reaches about 100 billion tons [1]. Specificity of the mining industry, i.e. management of non-renewable raw materials, degradation of the Earth's surface and generation of large amount of waste, means that it is perceived as one of the significant negative impacts on the natural environment [2, 3, 4, 5]. Therefore, this industry is one of those that awaits the most difficult challenges in the context of implementing the assumptions of sustainable development. The same concerns the KGHM Polska Miedź S.A., where the development of the company is based on the following five keystones: flexibility, efficiency, ecology, safety and sustainable development, e-industry and energy [6].

The global mining industry is responsible for about 6.2% of the world's energy consumption, the largest part of which (30%) is used in grinding processes [7]. With this in mind, one of the main directions set by mining companies in relation to sustainable development is to have their own sources of green energy [8, 9]. Striving to implement the strategy in this area also gives measurable economic, environmental and technological effects, allowing for the reduction of operating costs, improvement of energy security, access to green financing or development of innovative solutions.

To implement the assumptions of their sustainable development strategies, mining companies also develop and implement green technologies in the field of new methods of ore mining and processing. The potentially green technologies, most of which are at the development stage, are bio hydrometallurgical methods. A more promising direction combining aspects of processing and mining are in-situ bioleaching methods. Another application of bioleaching may be the recovery of elements from difficult-to-enrich sulfide polymetallic ores and their semi-finished products. Flotation tailings are the most problematic product of minerals beneficiation in terms of meeting the requirements of sustainable development. They usually make a stream of >90% of the ore directed to beneficiation, hence the possibilities of their full management are limited, and due to the low content of elements, their further processing often becomes economically unjustified. Lack of possibilities of waste management can be compensated by using this material as a construction material for Mining Waste Disposal Facilities, thus reducing the need to use other materials [10].

The above chapter aims to present the most important directions of development of the mining industry, which the mining companies are currently looking for as part of satisfying the assumptions of the sustainable development.

2. Green energy for the mining industry

The mineral mining industry, as a main source of metals, plays an important role in the energy transformation. Metals such as aluminum, cobalt, copper, lithium and nickel are important raw materials for manufacturing the batteries or photovoltaic panels. A significant share of these raw materials is obtained in the mining processes [11]. The production of these essential materials consumes a lot of energy, which is currently obtained mainly from non-renewable sources. Due to its high energy intensity and energy strategy, the mineral mining industry is also involved in green energy projects (Table 1).

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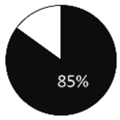
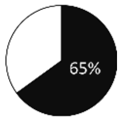
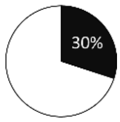
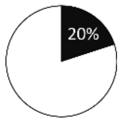
Table 1. Global examples of photovoltaic projects at mining industry plants

Reference	Plant	Country	Power [MW]	Covering the demand of the plant for electric energy [%]
[12]	Gabriela Mistral copper mine	Chile	35	
[13]	Gudai-Darii iron ore mine	Australia	34	
[14]	Evander w Mpumalanga gold mine	South Africa	10	
[15]	DeGrussa copper and gold mine	Australia	10	
[16]	KGHM Zanam	Poland	3,4	

35 MW Pampa Elwira project is an example of a photovoltaic installation providing electricity to a mining plant. One of the largest solar installations in the world is located in the Atacama Desert. It provides 54,000 MWh of thermal energy to the Chilean Gabriela Mistal copper mine owned by Codelco. The project replaces 85% of fossil fuels used in the process, reducing the combustion of diesel oil and reducing CO2 emissions by almost 15 thousand tons per year [12]. Using the oppressive hot climate of the area where the mine and processing plant are located, economic and environmental issues have been perfectly reconciled.

Another example of a solar power plant providing energy to a mine and processing plant is the photovoltaic installation operating for the Gudai-Daria iron ore mine in the Pilbara region in Australia. In 2021, a 34 MW photovoltaic farm was installed, consisting of approximately 10,000 solar panels. It was estimated that the solar power plant would cover 65% of the mine's average electricity demand, and even its whole demand during peak electricity generation periods. Additionally, installed together with a new lithium-ion battery energy storage system, the solar power plant reduces annual carbon dioxide emission by approximately 90,000 tons compared to conventional methods of generating energy from gas [13].

One of the KGHM Polska Miedź S.A. strategies is to reduce greenhouse gas emissions in the field of energy management and the use of renewable energy sources for its own plants [6] is the photovoltaic project at the KGHM Zanam plant in Legnica, Poland. The panels cover approximately half of the electricity required by the plant [16]. Currently, the Capital Group is planning further photovoltaic projects. At the beginning of 2024, a permit was issued for the construction of a photovoltaic farm for the Głogów Copper Smelter with a total installed power of 7.5 MW. Green energy from the sun is a strategic goal of KGHM Polska Miedź S.A. The energy transformation plans

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for 2030 assume at least 50% coverage of electricity from own sources, including renewable energy. This also allows for increasing energy independence and reducing the operating costs of the plants of KGHM [6]. A unique plant on a global scale with the most effective technological solutions related to energy acquisition is the Sierra Gorda copper mine. The Sierra Gorda mine, co-owned by KGHM Polska Miedź, is located in Chile in the Atacama Desert at an altitude of approximately 1,700 m above sea level. It manages a copper-molybdenum deposit, including both sulfide and oxide copper ores. The amount of energy needed to power the plant reaches 1,300 GWh per year. From January 2023, the Chilean mine will generate 100% of its electricity from renewable energy sources, such as solar, wind and hydropower installations. Using 100% of green energy eliminates approximately 1 million tons of CO2 emissions per year. This meets one of the main goals of the plant's development strategy, which is to minimize any potential negative impacts on the community and the environment [17].

The global economic crisis, the Russian invasion on Ukraine, which resulted in a dynamic increase in electricity prices (Fig. 1), increased the importance of renewable energy sources. Despite the increase in the prices of photovoltaic modules, energy from the sun on a utility scale is the least expensive option for newly generated electricity in the vast majority of countries around the world [18]. Approach of companies from the mineral industry includes plans to expand current designs of installations generating electricity from renewable sources and research on the technology, location and size of future potential possibilities to reduce carbon dioxide emission.

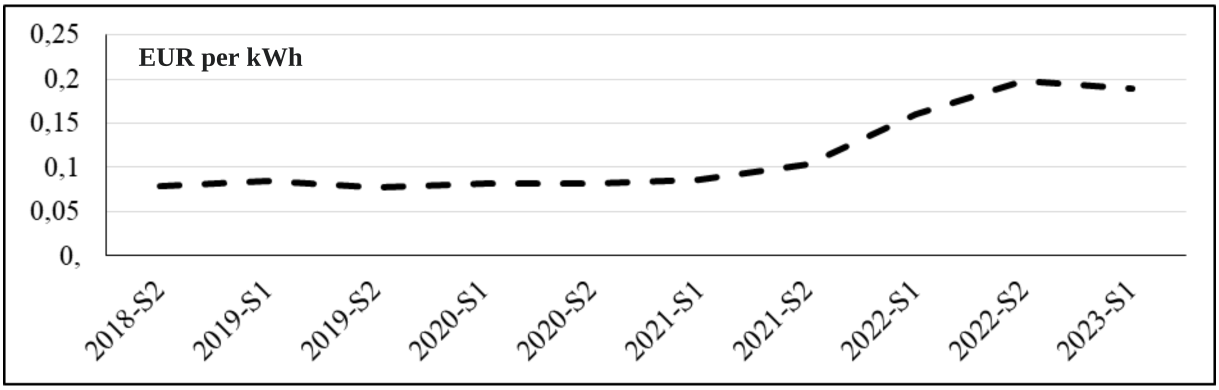

Fig. 1. Increase in electricity prices in 2018-2023 [19]

3. Green technologies in the mining industry

In the face of growing environmental challenges in the mineral industry, where mining and processing of raw materials are essential for industrial development, the green technology initiatives are becoming crucial [20]. The mineral industry must address the requirements of sustainable management of natural resources while maintaining operational efficiency and market competitiveness [20]. Green technologies cover a range of innovative solutions designed to minimize negative impacts on the environment, including not only renewable energy sources such as solar, wind, hydrothermal or geothermal energy, but also innovations in energy efficiency, waste management, and recycling [21]. Their common goal is to reduce greenhouse gas emissions, minimize pollution and manage resources sustainably. Environmental regulatory requirements and social expectations are becoming increasingly stringent, putting pressure on the industry to transform. Despite the obvious advantages, this process faces many obstacles, including the initial costs associated with the implementation of state-of-the-art technologies, the need for qualified staff to manage these technologies, and issues related to their availability [21]. The future of mineral engineering will certainly depend on the further implementation and development of green technologies. This approach is reflected in projects such as Bioshale and Biomore, which combine advanced technology with the needs of the environment and economy [22].

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The Bioshale project, co-financed by the European Commission, was initiated with the aim of developing breakthrough biotechnologies enabling the exploitation of ores containing valuable metals, such as copper (Cu), nickel (Ni), zinc (Zn) and other metals used in high-tech technologies, including noble metals such as silver (Ag) or platinum (Pt). It was crucial to take into account the challenges posed by the high content of organic matter and carbonates, which make the recovery of metals by conventional methods difficult [23].

The project, realized from October 2004 to December 2007, included research work on deposits in Talvivaara (Finland), not explored so far, deposits of Lubin (Poland) and Mansfeld (Germany), where extraction had ended and waste heaps remained. In the BIOSHALE project research work focused on limitations and possibilities of extracting the black shales. Attention was paid to testing and optimization of bioleaching processes for the extraction of metals from black shales, where recovery up to 98% copper from shale ore was possible in the bioleaching process, with use of microorganisms to extract elements, mainly metals from lean ores due to the natural ability of microorganisms to use inorganic compounds as a source of energy, while acidifying the environment, which makes many substances, including metals, soluble and easier to recover from ores. Equally impressive is the result of up to 92% silver recovery (PLINT process) [23]. The operations covered a wide spectrum of activities, from selection for strains of microorganisms with high biological activity, through laboratory experiments aimed at determining the optimal process conditions, to pilot tests and tests on an industrial scale. In the bioleaching process, even ores with low metal concentrations, which would traditionally be difficult and uneconomical to extract, can become a valuable source of raw material, which highlights the potential of this technique in comparison to traditional methods. Studies have copper cathodeslme shown that it is possible to increase the efficiency of metal recovery, which is a significant step forward in the development of ecological technologies for bioprocessing of black shale ores [24]. The diagram of the technology based on the Bioshale project concept is shown in Fig. 2 in a simplified way, demonstrating the key aspects and processes used in this method [25].

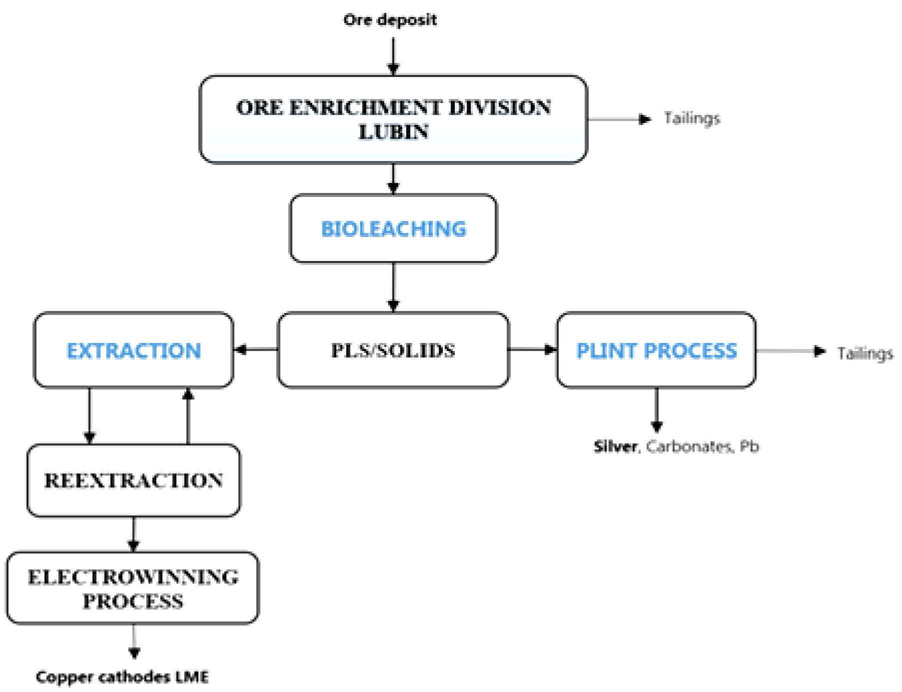

Fig. 2. Simplified diagram of Bioshale technology [25]

Another project, BIOMOre, initiated in 2015, introduces a new concept of metal extraction from deep ore deposits using biotechnology. BIOMOre was an initiative funded by the EU Horizon 2020 program, which aimed to develop a novel technology for metal extraction from deep ore deposits using biotechnology, including bioleaching. The three-year project brought together 23 partners from nine different countries, including five universities. The main role of microorganisms in this process was to generate Fe3+ ions in bioreactors placed on the surface and inject the solution into an injection well directly into the deep ore deposits. The leaching solution moves through natural flow paths in the deposit, which can be expanded by hydraulic fracturing. The metal-enriched solution (leachate) is then brought back to the surface through an extraction well [26].

Throughout the process, special attention was paid to waste minimization and designing the systems in a way that allows for their stability without environmental hazards. Within the BIOMOre project, numerous laboratory-scale and in situ tests were carried out to understand and optimize the process. Various parameters were verified, such as pressure and temperature on microorganisms and the kinetics of copper recovery. Specific experiments on deactivation and decontamination were also carried out to develop recommendations for eliminating the bacteria from deep underground ore deposits. The diagram below (Fig. 3) shows the concept of the surface and underground parts of the process. It is a visualization of the BIOMOre project concept, which aims to extract metals from deep ore deposits using biotechnology [26].

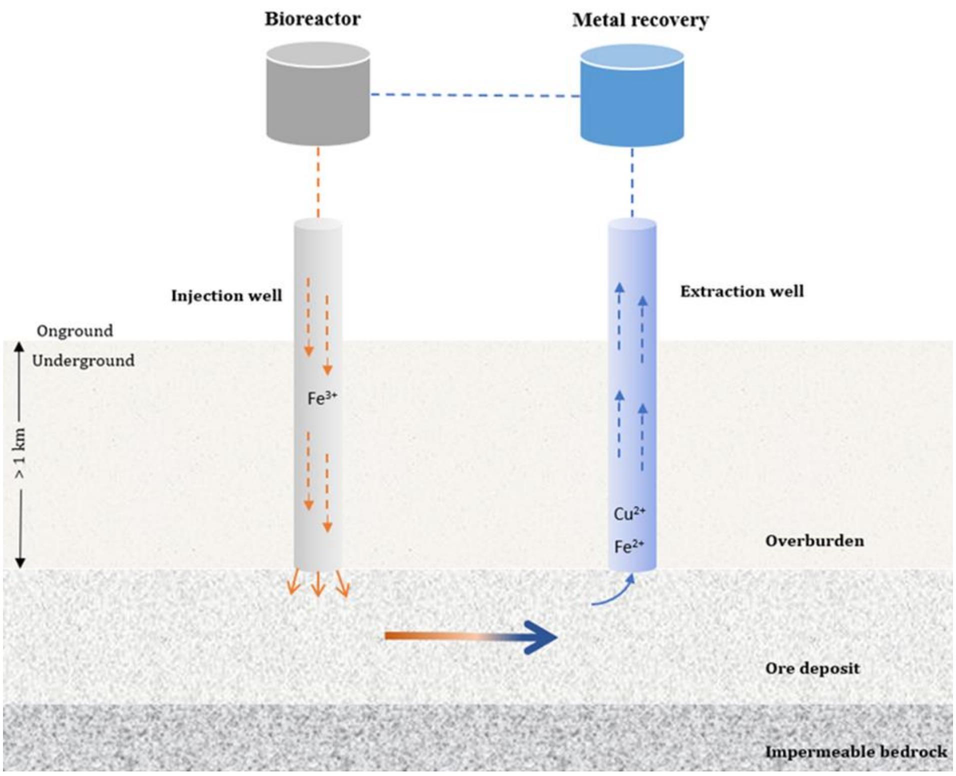

Fig. 3. Schematic diagram of the visualization of the BIOMOre project concept [26]

Both projects demonstrate the significant potential of biotechnology in the mining industry, offering alternative or complementary methods to traditional technologies. Through their activities, these initiatives contribute to the development of sustainable exploitation of mineral resources while offering new perspectives for resource exploitation with less negative impact on the environment.

Implementation and results of projects such as Bioshale and BIOMOre underline the key role of green technologies in the mineral industry, demonstrating that advanced biotechnologies can not only reduce the impact of mining processes on the environment, but also open up new economic opportunities for the mining sector. They also emphasize the need for continuous research work and development in the field of green technologies, which is crucial to achieving sustainable development in the mineral industry and, more broadly, in the global economy.

The bioleaching process has been implemented in various locations around the world in the mining industry, with some outstanding examples being the Udukona deposit located in Russia and the Talviaara deposit located in Finland.

The Udukona deposit, the largest copper deposit in Russia and the third largest in the world, has reserves of 26.7 million tons of copper [27]. The Udokan project uses advanced technology for processing oxidized, sulfide-oxidized and low-grade mixed ores. This technology includes stages such as stack bioleaching, combining pyro- and hydrometallurgical methods for ore processing [28]. Another important and most famous example is the Talvivaara deposit, where the bioleaching process was also implemented for processing polymetallic ores under extreme conditions of the North. The Talvivaara deposit became the first large-scale commercial operation of nickel sulfide stack leaching. This process included, among other things, crushing, screening and conditioning of the ore before leaching [29]. The first bioleaching lasts 13-14 months, after which the leached ore is transferred and re-stacked on the second-stage stacks. In the metal recovery process, metals are precipitated from the bioleach solution. Construction of the plant began in spring 2007 and the first metal sulfides were produced at the plant in October 2008. The development of the bioleaching process continued on an industrial scale, focusing on improving the permeability and aeration of the stack. Development of the bioleaching process at Talvivaara, starting with a pilot plant in 2005, contributed to improving the permeability and aeration of the stack, which in turn improved the leaching results. Despite initial challenges, the stack bioleaching process at Talvivaara has achieved its goals, becoming an example of successful extraction of metals from low-grade ores [29].

These examples demonstrate the application of bioleaching not only for more efficient extraction of metals from low-grade ores, but also as part of activities towards a more sustainable and environmentally friendly mining industry. These technologies are particularly relevant in the context of limited natural resources and increasing environmental awareness.

4. Tailings from flotation beneficiation of non-ferrous metal ores in the sustainable development strategy

The mining industry, as part of its core business, generates waste that falls into the category of non-renewable waste from industry (industrial waste) [30]. In the case of plants dealing with beneficiation of non-ferrous metal ores, flotation tailings are the main generated waste during production [31]. In the world literature, we can find examples of concepts for their management, with few actual implementations [32]. This is a significant stream of wastes in Poland, where industrial wastes are generated at the amount of 115 million Mg annually, they constitute the largest component representing 25.7% [33] (Fig. 4). Waste end flotation product in the processing plants of KGHM Polska Miedź S.A. makes over 99.5% of the waste stream from flotation beneficiation of non-ferrous metal ores.

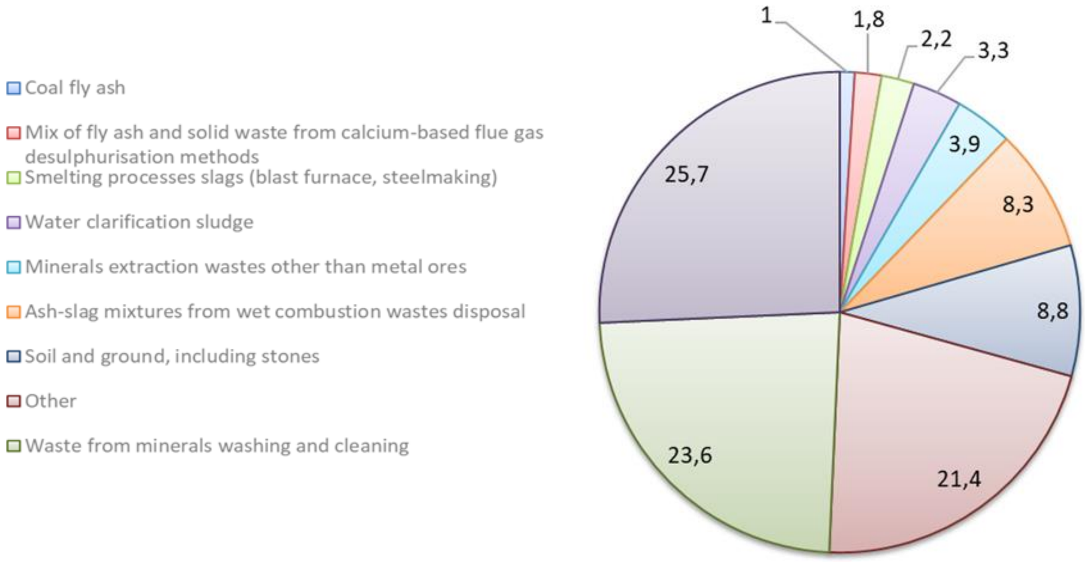

Fig. 4. Structure of generated wastes by their types in 2022

Such a high share of mining waste in the structure of industrial waste means that the sustainable development of the copper industry must refer to the aspect of their management in a sustainable manner. Currently, all waste is used to build and seal the Żelazny Most tailings storage facility. This reduces the need to use other materials for the facility over structure. Since the launch of operation, other possible forms of flotation waste management have been sought in a way that brings measurable effects for the natural environment and the company's financial results. One of the directions considered as part of striving for the above is the use of mining waste for the production of materials for construction purposes [10]. The possibility of using waste for these purposes is the subject of one of the projects implemented in the consortium of KGHM Cuprum sp. z o.o. Research and Development Center, Łukasiewicz Research Network - Institute of Ceramics and Building Materials and Metraco Sp. z o.o. The project is intended to manage 1 million Mg of flotation waste from current production per year. Other projects focusing on using this material for production of autoclaved concrete, aggregate for road construction, mineral fertilizers, or hydraulic backfill have realized for years [34, 35, 36]. Unfortunately, in most cases, the limitations that affect the possibility of implementing these solutions are the following:

- significant number of wastes to be managed,
- market absorption,
- meeting the quality requirements for commercial products,
- high investment cost,
- environmental and social restrictions.

Further recovery of minerals not extracted at the stage of beneficiation processes is another form of using the wastes [37]. In the non-ferrous metals industry, there are only few examples of using the technology for re-recovery of elements from flotation tailings. This is due to the specific properties of the minerals contained in this material as well as their grain size, which make their recovery in the beneficiation process difficult [38]. Tests in this area focused mainly on the recovery of copper and silver, due to their increased concentration in wastes, especially at the inactive Gilów and Wartowice OUOW facilities [39, 40]. Production of the elements concentrate from these wastes with their increased content could be realized by the hydrometallurgical methods. While the solutions at the technical and technological level requires efficiency of the process, they encounter problems related to the management of post-process waste, which in some cases may be classified as hazardous. However, taking into account the nature of these processes, this gives rise to problems resulting from environmental and social conditions [41]. This approach allows for the classification of OUOW as an anthropogenic deposit, which currently does not function in Polish legislation.

5. Conclusion

Projects involving renewable energy, bioengineering technologies, and waste management bring mining companies closer to the sustainable development goals defined by their strategies. One of the most recognizable examples of green energy production is the KGHM Polska Miedź S.A. Sierra Gorda Chilean mine, where 100% of energy consumption is supplied by renewable energy sources. The company also aims to supply 50% of its Poland-based operations with solar energy.

Biotechnologies for element recovery have been successfully implemented on an industrial scale in Finland and Russia. However, such solutions are not widely adopted globally due to high initial costs, their cutting-edge stage of development, and technological limitations. Nevertheless, companies continue to invest in biotechnology development because of its potential to reduce greenhouse gas emissions, minimize pollution, and promote sustainable resource management. One of the most intriguing projects is BIOMORE, which presented a new concept of metal extraction from deep ore deposits using biotechnology. The proposed technology, which is still under development, would allow metals to be extracted directly from deposits without the need for mine infrastructure construction, thus eliminating many of the negative aspects associated with traditional mining.

To further minimize the environmental impact of mining activities, companies are exploring new approaches for tailings utilization. This stream constitutes the majority of ore processed in flotation-based mining activities. A reduction in the volume of this waste stream might be achieved by using it as a material for the production of autoclaved concrete, aggregate for road construction, mineral fertilizers, or hydraulic backfill. One such technology, developed for carbonate tailings by KGHM Polska Miedź S.A., has a capacity of 1 million tons per year and was created during the FLOT-BUD project. This technology is still being refined and improved.

The completed projects are a strong contribution to future ideas and solutions for an increasingly sustainable mineral economy. Finding a balance between the environment, technology and economy is important in implementation of a given technology.

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Secondary separation of coking coal middlings in spiral separators

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Abstract:

The results of recovery by secondary separation tests of coking coal middlings are presented. The gravitational separation method, based on the differences in densities among the feed grains in the stream of flowing water, was used in the tests. Coking coal middlings, obtained in the three-product separation process in the coal fines jig of the processing plant of the coking coal mine in the Silesian Voivodeship, were tested. The following spiral separators were used during the separation process: Reichert LD-4 and Krebs 2.85. Based the test results, the most advantageous feed density was determined for each separator. Using the above-mentioned feed density, the concentrate of the lowest ash content and the highest waste output was obtained. The process was repeated for the optimal density to check how the grain classes of the feed separate in the secondary separation products containing coking coal interlayers.

Keywords: coking coal, spiral separators, coal interlayers

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1. Introduction

Due to the high content of impurities, raw hard coal is processed mechanically to increase the content of the useful component. Mineral processing includes classification, grinding, mixing with reagents (flotation), separation, dewatering or averaging [1].

The process of gravitational separation of raw hard coal enables its separation into a concentrate - a product with an increased content of a useful component, middlings and waste - a product with a reduced or trace content of a useful component [2]. In the case of interlayers in raw hard coal, the grains that are concretions of the useful component and waste rock, will be found in middlings. In most cases, the content of the useful component in middlings is insufficient for its industrial use.

The middlings, in the case of presence of interlayers, may be subjected to a grinding process to separate the useful component and waste rock. Then the ground material is directed to the secondary separation, to produce secondary concentrate, secondary middlings (in the case of threeproduct secondary separation) and secondary wastes. The secondary separation may be repeated many times, what is, however, determined by the economic analysis.

In the case of separation in the air, the grains of different densities are separated in a pulsating, often rising, air stream. This separation is mainly used for raw materials that are easily separable - with low density and without water. Such method has some ad-vantages and disadvantages. The lower quality of the end product compared to separation in the water medium is a disadvantage; dry product and low process costs are advantages [3]. As the content of interlayers in the raw material increases, the degree of separation difficulty increases, what requires using a medium of higher density, such as water [4].

2. Literature review

There is a large group of devices for beneficiation of minerals in a stream of water. These are machines, differing mainly in the direction of liquid movement, the distribution of forces acting on the grains in water, design solutions, and the way of collecting the products or feeding the material [5]. The method, in which the separation takes place in spiral separators, is one of the methods of gravitational separation in a water medium. In this method, the grains of different density are separated in a water stream [6].

A process of beneficiating the raw mineral is proceeded by preparatory activities i.e.: screening, crushing or classification. Their objective is to prepare the raw mineral in the way enabling to gain the maximal amount (concentration) of useful grains. In the majority of cases, for obtaining the optimum effect of separation, raw useful minerals, having not complicated characteristics, can be prepared for this process only once. However, quite often a single preparation of the mineral for a separation is not sufficient due to obtaining only a part of useful grains in the beneficiation process. The other part of these grains, as intergrown pieces or in other words the interlayers, is separated together with the dirt and after an appropriate further preparation it is subject to the secondary separation.

The grains of the dirt and of the useful mineral differ due to physical, chemical, electric, magnetic etc. properties which cause that their separation with use of many methods is possible. The bigger these differences, the easier it is to conduct the separation process and the obtained results are better.

Spiral separators are devices used for separation of fine-grained materials of different density and size [7, 8]. Fine-grained raw material, usually of the dimensions not exceeding 3 mm, can be used for separation. The lower grains size limit for low-density materials is 0.1 mm, and for high-density materials is 0.05 mm [9, 10]. A hydrocyclone can be used to remove grains below the lower limit of grains [11].

Apart from the subject of this article, KOMAG Institute of Mining Technology is also involved in other mining-related problems. The scope of KOMAG's activities also includes so-called urban mining, i.e. the recovery of valuable substances from urban waste. Currently, research is being conducted into the recovery of rare earth elements from WEE_NdFeB (waste of electronic equipment fitted with neodymium magnets) [12] or impregnated wood [13]. In addition, technical documentation is being developed for equipment used in urban mining such as shredders [14, 15].

3. Test objectives

Defining the most favourable feed density and determining the grain classes that are best suited for cocking coal recovery was the objective of tests described in this article. Intermediate product (middlings) containing interlayers from a pulse jig located in the selected coking coal processing plant, was the testing material. Two spiral separators were used in tests i.e. Reichert LD-4 and Krebs 2.85. Several separation tests were carried out at different densities to determine the most favourable feed density. Then, knowing the best density, the separation process was repeated. The grain size composition of the process products was analysed, along with the ash content in the grain classes. Based on the knowledge of the ash content in each grain class, the classes with the best grain separation efficiency were determined, i.e. those with a low ash content in the concentrate and a high ash content in the waste.

4. Grounds of separation processes in spiral separators

Spiral separators can be used for separation of fine-grained coal, iron ore, chromium, gold and sands containing heavy minerals [16, 17, 18]. They can also be used for the secondary separation of wastes from other processes [19, 20]. During a properly conducted process, the grains of the materials are separated according to their density.

The following two stages can be distinguished in the movement of any grain in the channel of the spiral separators [21]:

- the first stage, when the forces acting on the grain are out of balance, what results in a transient movement of the grain, both in the normal trough cross-sectional plane and along the trough; duration of this period depends on the physical properties of grains,
- the steady motion, when the forces acting on the grain are in balance; consequently, the grain moves at a constant speed along a helix path curvature.

Helical working through on which the feed flows - the suspension consisting of water and granular material – is the main working component of these devices [22]. The movement of the grains of the material consists of two following components [23]:

- the helical movement due to working through curvature and the pitch of the helix,
- the movement in the plane perpendicular to the trough surface, running through the centre of the trough curvature, as a result of which the depth of the suspension stream changes along the trough cross-section.

5. Methodology of recovery tests for determining the most favourable concentration, samples and used instruments

The tests were performed with use of middlings from a fine coal jig operating in a selected processing plant producing coking coal containing interlayers with the grain size of 30-0 mm. The weight of the taken sample was about 60 kg. Due to high water content, the tested material was initially dried, and then 25% of the material - 15 kg, were separated using the Jones divider. The obtained sample was analysed for its grain size distribution on a vibrating screen. In the result, 9 grain classes were obtained, which were tested to determine the ash content.

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The results are presented in Table 1. and Fig. 1. Based on the results, the grain size distribution curve was drawn together with the ash content in the given grain size classes.

Table 1. Grains size composition of raw material

Item	Grain class d [mm]	Output γ [%]	Ash content A [%]	Average ash content Aśr [%]
1.	>12	7.91	53.99	
2.	12-10	4.01	45.01	
3.	10-8	5.77	39.47	
4.	8-6	11.20	31.02	
5.	6-4	17.80	28.74	39.64
6.	4-3	8.65	29.22	
7.	3-2	12.33	31.10	
8.	2-1	14.58	40.20	
9.	<1	17.75	59.00	

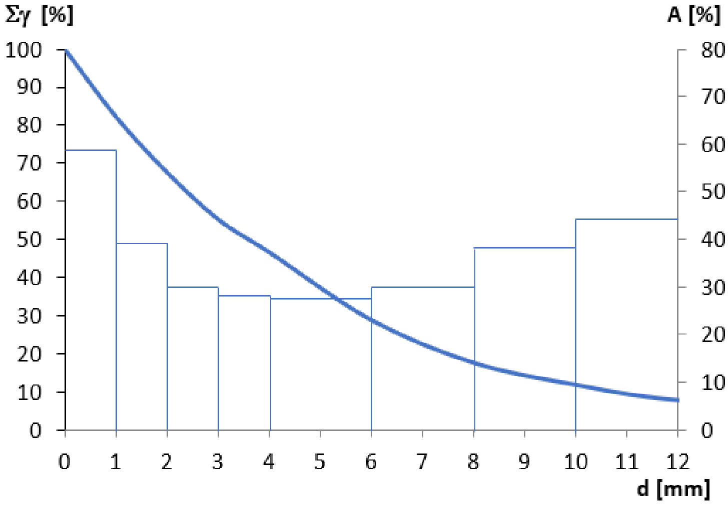

Fig. 1. Grain size curve with ash content in each grain class [own source]

After the tests, the previously separated 25% of the material were combined back with the rest of it. The material was then divided into two equal parts using the Jones divider.

The first part, weighing 28.6 kg, is hereinafter referred to as feed 1. This material was the feed for testing to determine the most favourable density. The feed 1 was crushed in a jaw crusher and then directed to the vibrating screen. The obtained product of crushing was screened on the vibrating screen of the mesh size 2 mm. The upper product of screening was sent to re-crushing on the jaw crusher. The bottom product from the vibrating screen and the crushing product were combined.

Next, the grain size distribution and the ash content of feed 1 were determined in each grain class. The results are presented in Table 2, Fig. 2 and used to plot the grain size composition curve together with the ash content in the given classes.

After considering the results of the former analyses, the separated grain classes of feed 1 were combined again. The material was sent for separation in spiral separators to determine the most favourable density.

Table 2. Grains size composition of feed 1

Item	Grain class d	Output γ	Ash content A	Average ash content Aśr
	[mm]	[%]	[%]	[%]
1.	>3	24.24	34.90	
2.	3-2	17.22	33.50	
3.	2-1	28.11	31.46	37.10
4.	1-0.5	16.90	44.19	
5.	<0.5	13.55	48.47	

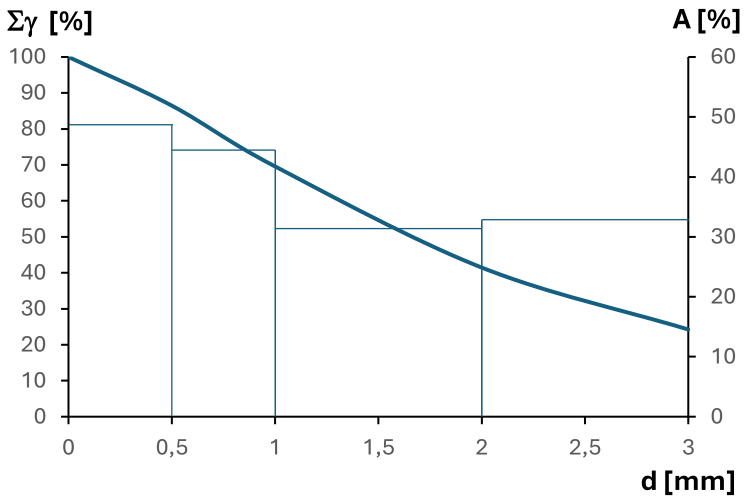

Fig. 2. Grain size curve of feed 1 after crushing at the given ash content in each grain class [own source]

The second part of the raw material weighing 28.6 kg is hereinafter referred to as feed 2. This material was sent for crushing in the laboratory jaw crusher. Then the material was analysed for grain composition using the laboratory vibrating screen. The obtained grain classes were tested for ash content, and the results are presented in Table 3 and in the diagram (Fig. 3).

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Table 3. Grains size composition of feed 2

Item	Grain class d	Output γ	Ash content A	Average ash content Aśr
	[mm]	[%]	[%]	[%]
1.	>3	10.05	35.88	
2.	3-2	17.05	33.00	
3.	2-1	24.03	33.53	43.66
4.	1-0.5	17.91	47.20	
5.	<0.5	12.49	51.98	

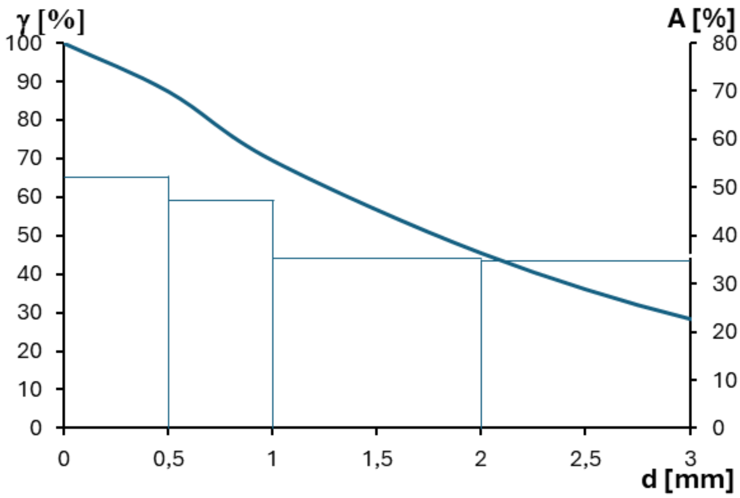

Fig. 3. Grain size curve of feed 2 after crushing at the ash content in each grain class [own source]

The Reichert LD-4 spiral separator was the first of the two devices used in the testing process. This device is designed for a separation of hard coal [6] and it had the following technical parameters [26]:

- spiral height: 2500 mm,
- spiral radius: 450 mm,
- coil width: 280 mm,
- coil inclination: 15°,
- number of coils: 6,
- width of the gaps between cutting tools successively 80 mm, 85 mm, 100 mm for lightweight, intermediate and heavy products,
- product collection: 3 outlets at the bottom of the separator and an additional heavy product collecting tray in the middle of the separator.

The device has two working troughs made of plastic, without any linings. The separator is equipped with a feeding tank and the feed is mixed by an agitator and compressed air. Mixing ensures a uniform dispersion of material particles in the feed and its constant density.

Krebs 2.85 separator was the second device used for testing and it had the following technical parameters [22]:

- spiral height: 1750 mm,

- spiral radius: 450 mm,
- coil width: 280 mm,
- coil inclination: 15°,
- number of coils: 2.85,
- width of the gaps between cutting tools 80 mm, 85 mm, 100 mm successively for lightweight, intermediate and heavy products,
- product collection: 3 outlets at the bottom.

This separator is equipped with two working troughs, 2.85 turns each. They are made of plastic without any linings. The feed is supplied from the same tank as in the Reichert LD-4 separator.

To determine of the most favourable concentration, feed 1 was used in the testing process. Concentrations of 300g/l, 350g/l and 400g/l were selected for separation in the Reichert LD-4 separator. After each separation test, excess water was poured out of the tanks, the separation products were collected and dried. Then, after drying, the separation products were weighed, representative samples were taken and the ash content was determined. Then, after sampling, the separation products were combined again and further tests for another concentration were conducted.

The concentrations of 300 g/l and 350 g/l were selected for separation in the Krebs 2.85 separator. Due a necessity of combining the separation products, the test for concentration of 400 g/l was abandoned, due to the partial loss of the finest grains fraction. After each separation test, excess water was poured out from the tanks and the separation products were collected and dried. Then, the separation products were weighed, representative samples were taken and the ash content was determined. Subsequently, the products were combined and the separation process was repeated at the next concentration.

6. Results of separation tests for determining the most favourable concentration

The results of the product analyses of separation tests in the Reichert LD-4 separator at the concentrations: 300 g/l, 350 g/l and 400 g/l are given in Table 4.

Table 4. Results of separation in the Reichert LD-4 spiral separator at concentrations: 300 g/l, 350 g/l and 400 g/l

Item	Separation product	Concentration 300 g/l		Concentration 350 g/l		Concentration 400 g/l	
		Output γ	Ash content A	Output γ	Ash content A	Output γ	Ash content A
		[%]	[%]	[%]	[%]	[%]	[%]
1.	Concentrate	24.82	18.88	26.27	19.73	34.19	21.36
2.	Middlings	32.73	28.17	37.80	32.04	43.95	35.90
3.	Waste	42.45	52.11	35.93	53.55	21.85	56.57
4.	Average ash content Aśr [%]	36.03		36.53		35.44	
5.		Separation time: 1' 13" 65'''		Separation time: 1' 04" 68'''		Separation time: 55" 83'''	

The results of the product analyses of separation tests in the Krebs 2.85 separator at the concentrations: 300 g/l, 350 g/l are presented in Table 5.

Table 5. Results of separation process in the Krebs 2.85 separator at concentrations: 300 g/l or 350 g/l

Item	Separation product	Concentration 300 g/l		Concentration 350 g/l	
		Output γ [%]	Ash content A [%]	Output γ [%]	Ash content A [%]
1.	Concentrate	30.11	20.10	26.64	19.52
2.	Middlings	40.87	30.27	36.26	27.52
3.	Waste	28.92	52.03	37.10	56.57
4.	Average ash content Aśr [%]	33.50		36.17	
5.		Separation time: 1' 20" 80"'		Separation time: 1' 11" 66"'	

7. Discussion of separation results at selected concentrations

Raw coking coal interlayers contain 39.64% of ash. The lowest ash content belongs to the 6-4 mm class and amounts to 28.74%, with output 17.80%. The highest ash content was found in the <1 mm class - it amounted to 58.98%, with the output in the class 17.75%. Also, grains >12 mm showed a high ash content of 53.99%, with an output of 7.91%.

The feed 1, used for a determination of the optimum concentration contained 37.10% of ash. The lowest ash content was found in the grain class 2-1 mm, amounting to 31.46%, with the output class of 28.11%. The largest grains >3 mm, representing 24.24% of the total given feed, contained 34.90% of ash. The smallest grains <0.5 mm showed the highest ash content, amounting to 48.47%, with the output of 13.53%.

In the Reichert LD-4 separator, the tests were conducted at concentrations of 300 g/l, 350 g/l, and 400 g/l. In the result of the separation tests, each time the separation products differed in their output and ash content.

Three products were obtained for the feed concentration of 300 g/l. The largest amount of material went to waste, 42.45% containing 52.11% of ash, the smallest amount of material went to the concentrate, 24.82 with the ash content of 18.88%. In turn, the out-put of the middlings was 32.73% and the ash content was 28.17%. The ash content in the feed, calculated from the balance equation, was 36.03%. The time from opening the feed tank to the flow of feed from the tank was 1 minute and 13.65 seconds.

At the concentration of 350 g/l, most of the material was transferred to the middlings i.e. 37.80% with the ash content of 32.04%. The smallest amount of material was transferred to the concentrate, i.e. 26.27% with the ash content of 19.73%. The waste output amounted to 35.93% with the ash content of 53.55%. The ash content in the feed was 36.53%. The feed flow time from the feed tank was 1 minute and 4.68 seconds.

The feed of the concentration 400 g/l was divided into three products. The highest output was observed for the middlings and it amounted to 43.95% with the ash content of 35.90%. The output of the concentrate was 34.19% and it contained 21.36% of ash. The lowest waste output was 21.85% with the ash content of 56.57%. The average weighted ash content in the feed was 35.44%. The feed flow time from the tank was 55.83 seconds.

For separation in the Krebs 2.85 separator, the feed concentrations of 300 g/l, 350 g/l and 400 g/l were assumed. During the tests, the separation test at the concentration of 400 g/l was abandoned

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because the material with each subsequent test had less and less fine grains. Fine grains were washed out when water was poured from containers for the separation products.

The test with the feed concentration of 300 g/l gave the following results: the highest product output was found in the middlings, amounting to 40.87%, the lowest output was obtained from waste 28.92% and the output of concentrate was 30.11%. The ash content was as follows: for concentrate 20.10%, for middlings 30.27% and for waste 52.03%.

Using the feed concentration of 350 g/l, the highest product output was obtained from waste 37.10% with an ash content of 56.57%. The lowest output was obtained for the concentrate, which was 26.64% and contained 19.52% of ash. The output for the middlings was 36.26%. The ash content of the middlings was 27.52%.

8. Conclusions concerning the impact of density changes on the products parameters

The tests enabled to analyse the secondary separation of middlings, containing coking coal interlayers, using the gravitational separation in water. Spiral separators: Reichert LD-4 and Krebs 2.85 were used in tests. By changing the feed density, a different separation of feed grains was reported. The products of different output and ash content were obtained. The lower average ash content in the products, obtained during the process, might depend on the way the products were collected. Each time the excess water was poured from the product tanks, a slight loss of the finest grains and those with the highest ash content might happen.

Increasing the feed density gradually every 50 g/l, from 300 g/l to 400 g/l and directing it to the Reichert LD-4 spiral separator, the following changes were observed:

- an increase of the concentrate output from 24.82%, through 26.27% to 34.19%,
- an increase of the ash content of the concentrate from 18.88%, through 19.73% to 21.36%,
- an increase of the output of middlings from 32.73%, through 37.80% to 43.95%,
- an increase of the ash content in middlings from 28.17%, through 32.04% to 35.90%,
- a reduction of waste output from 42.45%, through 35.93% to 21.85%,
- an increase of the ash content in the waste from 52.11%, through 53.55% to 56.57%.

Knowing the above relationship, the following conclusion can be formulated: the optimum concentration of the feed for separation in the Reichert LD-4 separator is 300 g/l. At this density, the concentrate with the lowest ash content and the highest amount of waste was obtained.

In the case of the Krebs 2.85 separator, by increasing the concentration from 300 g/l to 350 g/l, the following changes were observed:

- a decrease in concentrate output from 30.11% to 26.64%,
- decrease in ash content from 20.10% to 19.52%,
- a decrease in middlings output 40.87% to 36.26%,
- a decrease in ash content in the middlings from 30.27% to 27.52%,
- an increase in waste output from 28.92% to 37.10%,
- an increase in waste ash content from 52.03% to 56.56%.

Knowing the above relationship, the following conclusion can be formulated: the optimum feed density for separation in the Krebs 2.85 separator is 350 g/l. At this density, the concentrate with the lowest ash content and the highest amount of waste was obtained.

9. Methodology and results of recovery tests for determining the most advantageously separating grain classes

In this part of testing, feed 2 was used. First, an attempt was made to separate the material in the Reichert LD-4 spiral separator. The previously determined, best density was used - 300 g/l. Then, the separation products were analysed in terms of the grain composition using the laboratory vibrating screen. The separation products were analysed regarding the ash content and the results are presented in Table 6. After analysing the separation products, they were combined to obtain the feed for the next separation test in another spiral separator.

Table 6. The analysis results of the grain size distribution and ash content for each grain class of separation products obtained in the Reichert LD-4 separator

Item	Separation product	Concentrate		Middlings		Waste	
		Output γ	Ash content A	Output γ	Ash content A	Output γ	Ash content A
		[%]	[%]	[%]	[%]	[%]	[%]
1.	>4	18.48	27.68	29.03	42.32	6.60	44.21
2.	4-3	16.30	27.03	9.12	40.73	4.57	46.30
3.	3-2	21.74	26.16	22.97	39.14	7.11	49.29
4.	2-1	27.17	16.30	21.07	36.11	23.86	53.71
5.	1-0.5	7.61	12.19	12.79	25.39	33.50	60.74
6.	<0.5	8.70	22.47	5.02	23.76	24.37	62.39
7.	Total	30.65	22.52	32.81	37.04	36.54	56.90
8.	Average ash content Aśr [%]	39.11					
9.		Separation time: 1' 11" 80"'					

Subsequently, the test was conducted in the Krebs 2.85 spiral separator. The previously determined most favourable concentration - 350 g/l was used. Then, the grain size distribution and ash content of the separation products were analysed. The results are presented in Table 7.

Table 7. The results of the grain size analysis and ash content for each grain class of separation products in the Krebs 2.85 separator

Item	Separation product	Concentrate		Middlings		Waste	
		Output γ	Ash content A	Output γ	Ash content A	Output γ	Ash content A
		[%]	[%]	[%]	[%]	[%]	[%]
1.	>4	15.95	21.69	15.53	29.06	6.39	39.92
2.	4-3	15.23	22.73	8.96	33.59	4.68	41.51
3.	3-2	22.08	24.56	19.23	33.27	9.56	46.91
4.	2-1	22.22	16.87	29.67	28.12	28.56	49.72
5.	1-0.5	8.75	12.97	16.83	21.37	25.63	57.61
6.	<0.5	15.77	27.46	9.79	30.53	25.19	59.12
7.	Total	23.99	21.56	37.03	28.85	38.97	52.83
8.	Average ash content $A_{śr}$ [%]	36.45					
9.		Separation time: 1' 17" 24"'					

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10. Discussion of the results of the best separation efficiency grain classes

The analysis of tests results of the feed 2, after crushing, showed 43.66% of ash. The highest ash content was found in grain size class - <0.5 mm and it amounted to 51.98%, with the output of 12.49%. The lowest ash content was found in the grain size class 3-2 mm and it amounted to 33.00%, with the output of 17.05%.

The separation test was conducted at the most favourable density of 300 g/l in the Reichert LD-4 spiral separator. Three different products were obtained and their grain size distribution and ash content in the given grain classes were analysed.

In the first separation product, i.e. the concentrate, the ash content was 22.52% at the lowest output of 30.65%. The largest amount of grains, in relation to the product, was in the grain size classes 2-1 mm (27.17%) and 3-2 mm (21.74%) containing respectively 16.30% and 26.16% of ash. The concentrate contained the smallest amount of grains in classes <0.5 mm (8.70%) and 1-0.5 mm (7.61%), containing respectively 22.47% and 12.19% of ash. The grain classes 1-0.5 mm and 2-1 mm contained the smallest amount of ash, 12.19% and 16.30%, respectively. In turn, the largest amount of ash, 27.03% and 27.68%, was found in the grain classes 4-3 mm and > 4 mm.

In the second separation product, the middlings, the ash content was 37.04% with output 32.81%. The highest output of grain size class was found in classes > 4 mm (29.03%) and 3-2 mm (22.97%), containing respectively 42.32% and 39.14% of ash. The smallest amount of grains was in the grain size classes 4-3 mm (9.12%) and <0.5 mm (5.02%) and they contained 40.73% and 23.76% of ash. The highest ash content was found in classes > 4 mm and 4-3 mm, on the level of 42.32% and 40.73%, respectively. In turn, the lowest ash content was found in grain size classes <0.5 mm and 1-0.5 mm, containing 23.76% and 25.39%, respectively.

When testing the third separation product, the waste, the highest output, amounting to 36.54%, and ash content of 56.90% were reported. The majority of grain classes in the waste belongs to the classes with the highest ash content. These classes are <0.5 mm with an output of 24.37% and ash content of 62.39% and 1-0.5 mm with an output of 33.50% and ash content of 60.74%. Also, the lowest output of grain classes in the waste was in the class with the lowest ash content, i.e. classes 4-3 mm and > 4 mm. For the 4-3 mm class, the output of the grain class in the product was 3.47% and the ash content was 46.3%. For the class > 4 mm, the output and ash content was 6.6% and 44.21%.

Using the previously selected, most advantageous concentration of 350 g/l, the test was conducted in the Krebs 2.85 spiral separator. In the result of this process, three different products were obtained. They were analysed in terms of ash content, output, grain composition and ash content in grain size classes.

The lowest product output was the concentrate 23.99%, at the ash content level of 21.56%. Grain size classes 2-1 mm (22.22%) and 3-2 mm (22.08%) had the highest product output. On the other hand, classes 1-0.5 (8.75%) mm and 4-3 mm (15.23%) had the smallest output of concentrate. Grain classes 1-0.5 mm and 2-1 mm had the lowest ash content which amounted to 12.97% and 16.87%, respectively. The highest ash content was found in grain size classes <0.5 mm and 3-2 mm and amounted to 27.46% and 24.56%, respectively.

In the second separation product, the middlings, the ash content was 28.85% with an output of 37.03%. The highest content of the output of grain classes in the product was measured in classes 2-1 mm (29.67%) and 3-2 mm (19.23%). In turn, the lowest output of grain classes was determined for classes <0.5 mm (9.79%) and 4-3 mm (8.96%). The highest amount of ash was found in the grain classes 3-2 mm and 4-3 mm, i.e. 33.27% and 33.59%. The smallest amount of ash was found in grain classes 1-0.5 and 2-1 mm, i.e. 21.37% and 28.12%.

When testing the third product of separation, the waste, the highest output was measured for classes 1-0.5 mm (25.63%) and 2-1 mm (28.56%). The lowest output was found in classes 4-3 mm and >4 mm and it amounted to 4.68% and 6.39%, respectively. The highest ash content was determined for grain classes <0.5 mm and 1-0.5 mm, i.e. 59.12% and 57.61%, respectively. The lowest ash content was determined for classes 4-3 mm and >4 mm and it amounted to 41.51% and 39.92%.

11. Conclusions concerning the impact of density changes on the products parameters

The grain size composition tests, including a determination of ash content in grain classes, and their analyses enabled to find the grain classes of the feed that have the best separation efficiency. Using different spiral separators for the feed density of 300 g/l, a different grain distribution of the tested material was observed. Products that differed in ash content and output, were obtained.

Knowing the grain composition of the material separation products on both spiral separators, the conclusions concerning the following aspects were drawn:

- the output of grain classes in separation products:
    - grains > 2 mm give higher output in the middlings and concentrates,
    - grains 2-1 mm give similar output in separation products,
    - grains 1-0.5 mm give higher output in the middlings and waste,
    - grains < 0.5 mm give higher output in the waste and concentrate,
- the ash content in classes of grain separation products:
    - larger grains have lower ash content in the waste than smaller ones,
    - the lowest ash content in the concentrates was in grain classes 2-1 mm and 1-0.5 mm grain classes,
    - the highest ash content in the middlings was in the 4-3 mm grain class,
    - the lowest ash content in the middlings was in the 1-0.5 mm grain class,
    - the smallest difference in ash content between the separation products was in the > 4 mm class, for the Reichert LD-4 spiral separator it was 16.53% and for the Krebs 2.85 spiral separator it was 18.23%,
    - the largest difference in the ash content between the separation products was in the 1-0.5 mm class, for the Reichert LD-4 separator – 48.55% and for the Krebs 2.85 separator – 44.64%,
    - the 1-0.5 mm grain class was separated most favourably, because it had the lowest ash content in the concentrate and in the middlings and the highest one in the waste, among all the grain classes.

Analysing the results of separation products from the Reichert LD-4 and Krebs 2.85 spiral separators, it was found that the grain classes 4-3 mm and > 4 mm had the worst separation efficiency. In total, these classes achieved the highest ash content in the concentrate and in the middlings, and the lowest one in the waste.

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Elektric rotary-percussion drilling machine of high power – feasibility study

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Abstract:

Rotary-percussion drilling machines are commonly used for drilling hard-to-cut and abrasive rocks. Currently, in underground mining, drilling jumbos with hydraulic drilling machines and rotary percussion drilling machines are used in chamber-and-pillar systems. The article presents results of the work aimed at assessing the technical possibilities of creating an electric rotary-percussion drilling machine with the parameters of currently used hydraulic drills. The biggest challenge is to obtain high impact energy and frequency as well as rotation speed and torque while limiting the weight and size of the drilling machine. The required parameters of the electric drilling machine were the parameters of the hydraulic drilling machines used at KGHM Polska Miedź S.A. Known and applicable design solutions for electric drilling machines were analysed including the reported inventions in Poland and abroad. Then, three design solutions were selected and dynamic model tests were carried out, the main goal of which was to estimate the required torque, which, combined with the rotation speed, determines the power of the electric motor. As a result, the solution was obtained, which in terms of weight and dimensions does not differ significantly from the hydraulic drilling machines, while at the same time enabling the achievement of similar operational parameters that determine the mechanical drilling speed.

Keywords: simulation tests, rotary percussion drilling machine, hydraulic drilling machine, electric drilling machine, underground mining,

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1. Introduction

Rotary percussion drilling machines use different drives to generate impact and rotation. There are known the solutions for hydraulic, pneumatic and electric drilling machines. However, drilling machines used on the drilling jumbos are expected to have high impact energy and frequency with high torque. Only hydraulic drills meet these requirements. However, for much lower parameter values, pneumatic or electric solutions are used.

There are known the solutions for mine electric drilling machines, but due to a number of disadvantages, especially big weight, large dimensions and high failure rate, they were not developed and were quickly replaced by hydraulic drilling machines [1]. Electric rotary-percussion drilling machines have not the parameters of hydraulic drilling machines, which are crucial in mining processes. However, in the case of drilling machines used in the construction, road and private use industries, electrical solutions are very popular. In the case of mining solutions, in recent years only one electric drilling machine was available, but with a low impact energy.

2. Analysis of state of the art

A review of patent publications allowed us to find technical solutions and utility models in the field of electric rotary percussion drilling machines. These solutions can be divided into three types. The first are the solutions that create an impact effect using various types of cams connected to a coil spring. These solutions are mainly used in hand-held power tools with low weight and relatively low impact energy. These patents belong to global companies specializing in the production of power tools, such as Makita Corp, Robert Bosch GmbH, or Black&Decker.

Another type of solutions are the devices using the magnetic field. Electromagnets generate impact piston impacts, and the electric motor is responsible for the spindle rotation. These inventions therefore require power supply for both electromagnetic units and the electric drive that rotates the tool. This solution is used, for example, by FlexiDrill.

The last type are solutions that cause a stroke by a moving piston in a cylinder with a spindle at the end. The electric drive, through a gear unit, rotates the crankshaft to which the piston is attached. This piston presses on the spindle, not directly, but through a coil spring or air cushion, which protects it against direct impacts. In these inventions, the same electric drive causes the impact and rotates the spindle. HILTI is one of the companies using such a solution.

Of all types of inventions, where the impact is generated by a crankshaft and a piston with an air cushion were included in further analysis. This solution offers relatively greatest performance with a relatively simple and well-known design. However, for the research purposes, two other solutions were also considered: with a shaft and an inclined disc and with an electric linear motor. For the first solution, the drive shaft has a disc with a pin at an angle in relation to its axis. The disc with a pin is installed on a shaft. The rotation of the shaft causes a change in the angle of inclination of the disc, as a result of which the end of the pin moves back and forth. The movement is transmitted to the piston. The piston is separated by an air cushion with a impact piston of a specific mass. The piston drives the impact piston, which hits the rod holder. The same shaft simultaneously transmits torque to the rod holder, generating continuous rotation. The third solution is to use two electric motors, one rotary and the other linear. They generate the impact of the ram and the rotation of the tool independently.

Mine electric rotary-percussion drilling machines were historically used for a very short time. This was related to their disadvantages, the solution of which was not sought because hydraulic drilling machines were devoid of them. An example of this is the Pneumelectric drilling machine (Fig. 1). Generally, each electric drilling machine had a crankshaft with a connecting rod that generated a reciprocating movement. In the initial solutions, the piston and the impact piston were separated by a spring, and in later solutions, as now, by an air cushion.

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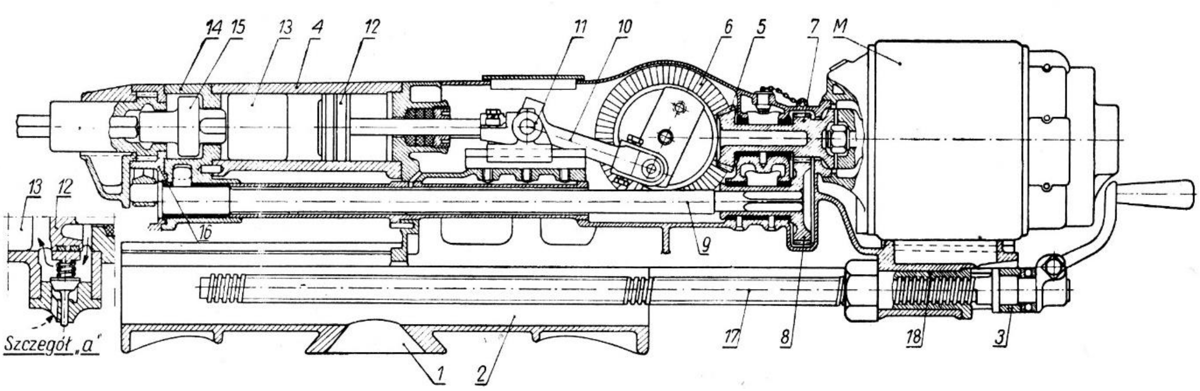

Fig. 1. Mine electric rotary - percussion drilling machine Pneumelectric [2]

In 2018, the start-up Lekatech was founded in Finland. Lekatech offers an electric impact hammer mounted on excavators. According to the company, the technology used is significantly better than the hydraulic hammers. A Linear Induction Motor (LIM) was used, which is the most important component of the hammer. The advantage of the hammer is the ability to control the impact energy and frequency of impacts. The hammer has a high impact energy up to 1500 J, but with a very low frequency from 1 Hz to 15 Hz and a large mass of approximately 450 kg [3, 4].

Currently, there is a well-known mine electric rotary-percussion drilling machine with a crankshaft - Hilti TE MD-20, shown in Fig. 2. It is a drill powered by an asynchronous motor with a low power of only 2.2 kW. According to the catalogue, the energy of a single impact is 28 J and the torque is 100 Nm. The tool moves at a rotational speed of 205 rpm. The drilling machine weighs 23.5 kg and is a hand-held drilling machine, but operated from a support [5].

However, in the literature, only some studies can be found in the field of simulations and general model tests of rotary percussion drilling machines [6, 7, 8]. There are many studies available on dynamic simulation studies of mining machines [9, 10, 11].

Fig. 2. Hilti TE MD20 drill and 3D model of the drill mechanism from the Hilti catalogue [2]

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3. Assumption for the electric rotary percussion drill

Feasibility study of a high-power electric rotary-percussion drilling machine was the work objective. As well as estimating the power of the electric motor and determining approximate overall dimensions and minimum weight. Hence, the model was developed using a number of simplifications that, to a greater or lesser extent, affect the obtained results. The simplifications were adopted in such a way as to obtain the best possible results. Therefore, many unfavourable phenomena, such as air flow resistance or friction of interacting components, were omitted. The results of the simulations should be treated as indicative. Due to the assumptions, in reality the drilling machine will not achieve the expected parameters for the assumed power. This means that the specified power is the minimum required for ideal conditions. Similarly, regarding the size and weight of the drilling machine, the estimates given are a lower limit.

Important is the method for determining the impact energy of the drilling machine. Manufacturers determine the impact energy in different ways, measuring it at the measuring stations or determining its value based on the mass and speed of the impact piston. As part of the work, the model tests were carried out, so taking into account the lack of detailed information on the method of determining the impact energy by various manufacturers, the impact energy was defined as the kinetic energy of the impact piston with mass m_b and velocity v_b at the moment of impact, as:

$$E_u = \frac{m_b \cdot v_b^2}{2} \text{ [J]}$$

Many different solutions for electric rotary percussion drilling machines are known, especially among patents. In practice, only two main solutions are used - with a crankshaft and with an inclined disc, and such solutions have been analysed. Additionally, use of a linear motor, as in the above-mentioned impact hammer has been analysed.

The first stage of the work was to determine the parameters of the electric drilling machine based on data from hydraulic drilling machines used at KGHM Polska Miedź S.A. and which meet the expectations when drilling the blast holes. The key parameters are the energy and frequency of the impact as well as the speed and torque of the tool. For comparison purposes, weight of the drilling machine is also important. Several model+s of drilling machines were analysed and the following parameters were collected based on the catalogues:

- MM-20 f = 67 Hz, M = 796 Nm, n = 250 rpm, E=400-500 J, m = 177 kg
- HC109 f = 40-60 Hz, M = 1000 Nm, n = 190-220 rpm, E=440 J, m = 142 kg
- HC109 f = 40-60 Hz, M = 457-1275 Nm, n = 120-300 rpm, E=449 J, m = 142 kg
- HC95LQ f =57 Hz, M = 764-955 Nm, n = no data, E=430 J, m = 196 kg

From the point of view of the impact mechanism operation, the most important assumption was to assume the required mass of the impactor, its stroke and speed at the moment of impact. This information is difficult to be obtained. Taking into account the diagram of the MM-20 drilling machine available in the catalogue, it was determined that the steel ram for this size weighs approximately 6.7 kg. Based on the analysis of available literature in this area, these parameters, including the speed of the impact piston at the moment of impact, were confirmed.

One of the articles presented the results of testing the hydraulic percussion drilling machine (Fig. 3) [12]. Based on these results, it was determined that for a 5 kg impact piston, the stroke is 53 mm, the maximum impact piston speed is 12 m/s (at the moment of impact), and the impact frequency is about 60 Hz ÷ 65 Hz.

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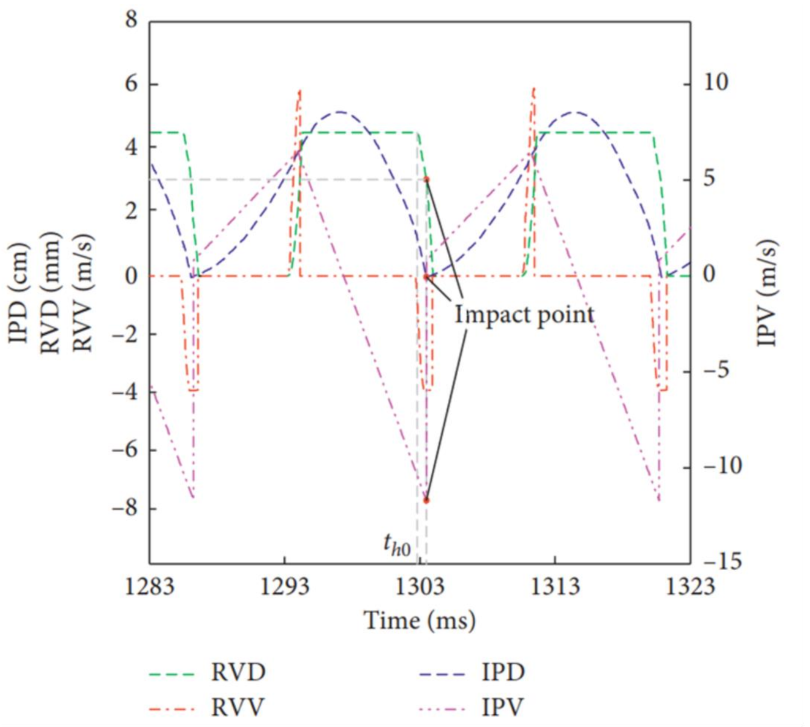

Fig. 3. Results of testing the hydraulic rotary-percussion drilling machine [12]
IPD: impact piston displacement); IPV: impact piston velocity; RVD: reversing valve displacement RVV: reversing valve velocity

Due to the above, the following parameters of the electric rotary-hammer drilling machine were adopted:

- impact frequency f = 60 Hz,
- impact energy E = 450 J,
- tool rotation speed n = 250 rpm,
- tool torque M = 800 Nm,
- impact piston weight 6.8 kg,
- speed of the impact piston at the moment of impact 11.5 m/s,
- ram stroke 60 mm (as an approximate value,
- speed at the moment of impact is of key importance).

4. Dynamic simulations

Based on the analysis of known design solutions of drilling machines, three concepts of an electric rotary-percussion drilling machine were developed. One of the concepts corresponds to the structure used in the Hilti TE MD20 drilling machine, hence, in the first stage, simulation tests of such a solution were carried out to verify the model and the parameters provided by the manufacturer. The design and parameters were determined based on available information [5]. After verifying the research methodology on this basis, model tests of an electric drilling machine were carried out for three different structures. The tests were conducted in the dynamic simulation module of Autodesk Inventor Professional.

The solutions developed and intended for simulation tests are the drilling machines, with the following characteristic components:

- a motor responsible for rotation and linear motor responsible for impact,
- a motor responsible for rotation and impact via a shaft with an inclined disc,
- a motor responsible for rotation and impact via the crankshaft.

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The parameters of the drilling machine were determined, and then, similarly to the Hilti drilling machine, various combinations of parameters were analysed. Additionally, motors of different power were tested to select the appropriate one. The initial simulations included the simplest air cushion model, and finally the Boyle-Mariotte law was used, which allowed for the determination of the nonlinear characteristics of the air cushion using the appropriate assumptions.

For each simulation, the path and speed of the impact piston, the rotational speed and torque of the electric motor, and the length and force of the spring that simulated the behaviour of the air cushion were plotted (Fig. 4). The key was to achieve the assumed impact frequency of 60 Hz and the required impact speed of 11.5 m/s at the moment of impact, which guaranteed achieving the calculated impact energy of 450 J.

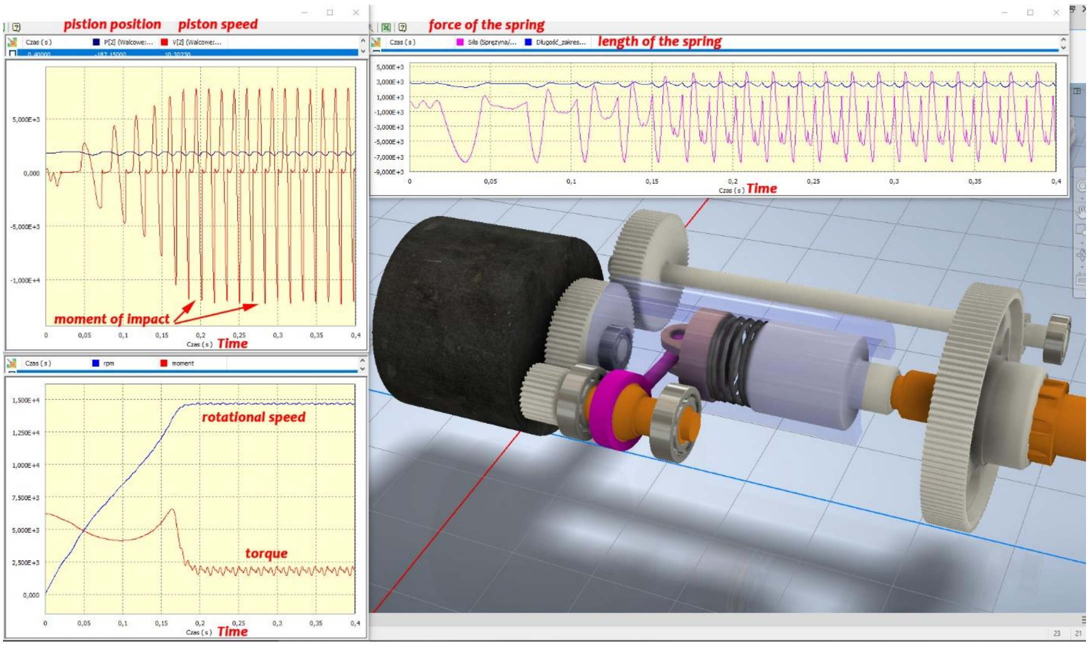

Fig. 4. An example screenshot from a dynamic simulation

4.1. Drilling machine with a linear motor

The first solution of the drilling machine was to use a rotating motor to generate rotational motion and a linear motor to generate impact. Taking into account the torque and rotational speed, an induction electric motor with a power of 22 kW and gears with a ratio of i = 5.8 were selected. The 22 kW motor itself weighs 172 kg. They were looking for a linear motor from different manufacturers. A SEW motor was selected, but the largest linear motor, SEW SL2P100ML, for an impact piston weight of 6.8 kg, allowed to generate a movement with a stroke of approximately 60 mm at a frequency of 9 Hz, which was too low. Moreover, for such a frequency, the impact piston does not achieve a speed of approximately 11.5 m/s, but only 1.7 m/s, which results in an impact energy of approximately 9.8 J. Hence, this solution was rejected.

4.2. Drilling machine with an inclined disk –asynchronous motor

Then, power requirement for an electric drilling machine with an inclined disc was checked. This solution assumed mounting the motor along the drilling machine, which allowed for impact and rotation without the need to use an angle gear. The gear ratios of the subsequent stages were selected to achieve a simultaneously impact frequency of f = 60 Hz and a tool rotation speed of approximately 250 rpm (Fig. 5).

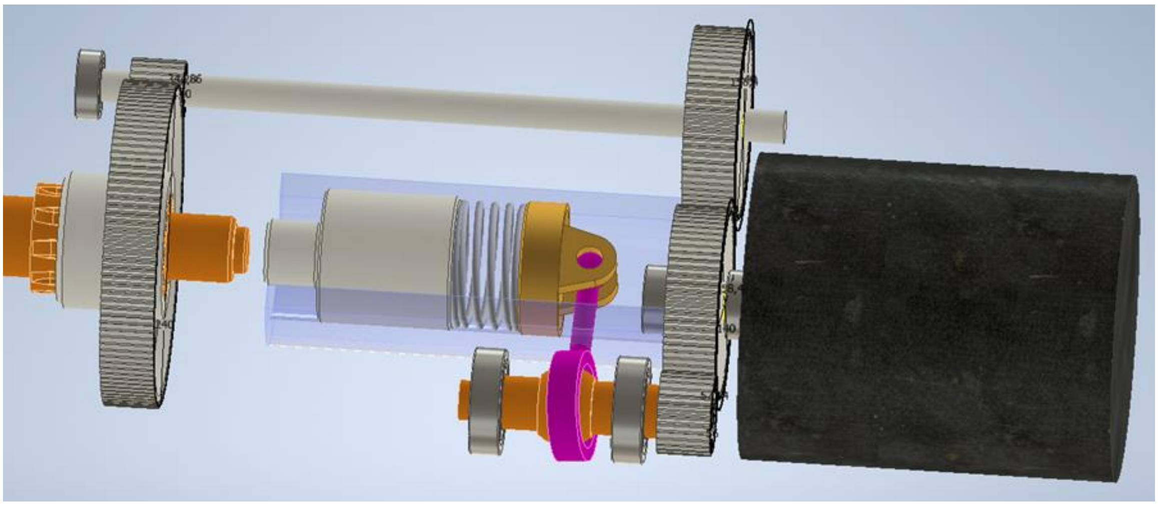

Fig. 5. 3D Model – electric percussion drilling machine with an inclined disk f = 60 Hz

For a 30 kW motor, in stable operation the torque demand was N = 145 Nm ÷ 216 Nm, and the motor operated in the speed range of 1461 rpm ÷ 1473 rpm, which is the operating point according to the catalogue of the selected motor. Hence, a 30 kW motor is sufficient in this solution (Fig. 6).

There are the following drilling machine parameters for a solution with an inclined disc and a 30 kW motor:

- multiplier from 1475 rpm to 3615.96 rpm – approx. I = 0.408 -> f = 60.25 Hz,
- reducer from 3615.96 rpm to 1466 rpm – approx. I = 2.466,
- reducer from 1466 rpm to 244 rpm – approx. I = 6,
- nominal tool rotation speed n = 244 rpm,
- torque from cutting N = 142 * 0.408 * 2.466 * 6 = 1171.13 Nm,
- impact frequency f = 60 Hz,
- impact piston weight 6.8 kg,
- maximum linear speed of the impact piston 12.7 m/s,
- computational impact energy: 548 J.

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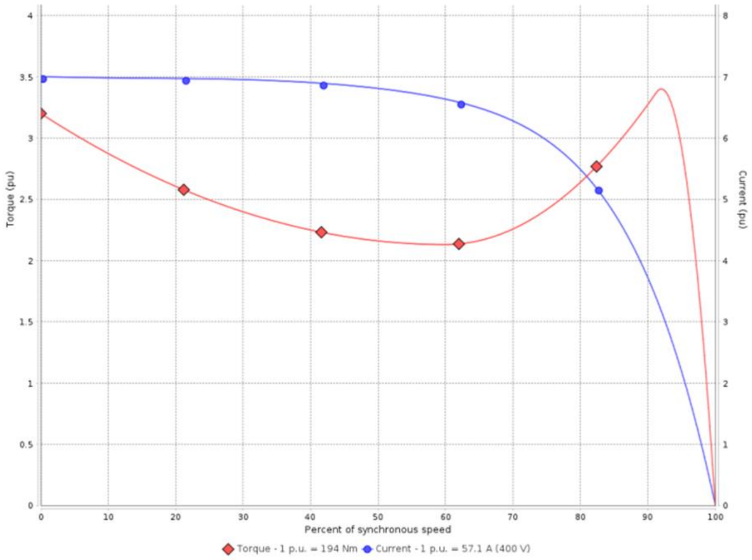

Performance	: 200/400/690/400 V 50 Hz 4P		
Rated current	: 114/57.1/33.1/57.1 A	Moment of inertia (J)	: 0.3743 kgm²
LRC	: 7.0	Duty cycle	: S1
Rated torque	: 194 Nm	Insulation class	: F
Locked rotor torque	: 320 %	Service factor	: 1.00
Breakdown torque	: 340 %	Temperature rise	: 80 K
Rated speed	: 1475 rpm	Design	: N

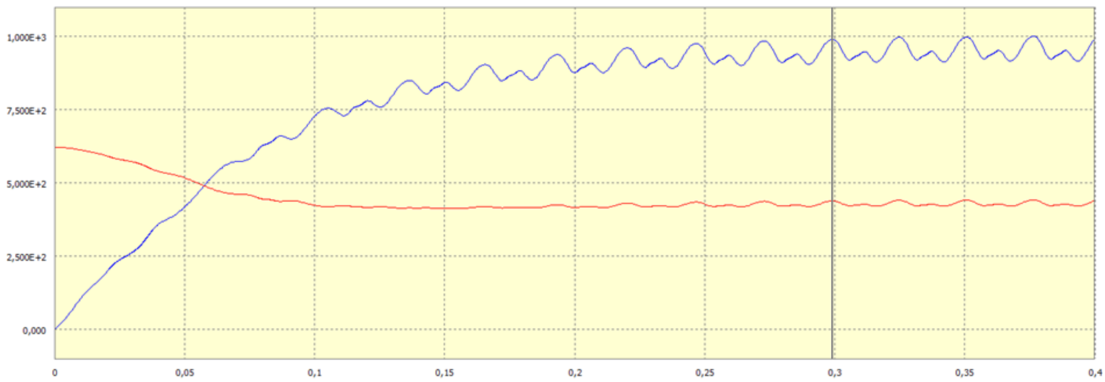

Fig. 6. Characteristics of 30 kW 200M/L motor and curves of speed and torque for a drilling machine with an inclined disk

The mechanism with an inclined disc is more complicated, what means that it may be too unreliable for the target drilling machine with high impact energy, that is why work on this solution was not continued.

4.3. Drilling machine with a crankshaft – asynchronous motor

The next analysed solution was a drilling machine with a crankshaft and, similarly to the Hilti drilling machine, mechanical gears. The model was developed to get the required parameters of the drilling machine. Thus, first the multiplier was used, then the reducing angular gear and the cylindrical reducer. For each analysed motor, its mechanical characteristics and rotor moment of inertia were taken into account (Fig. 7).

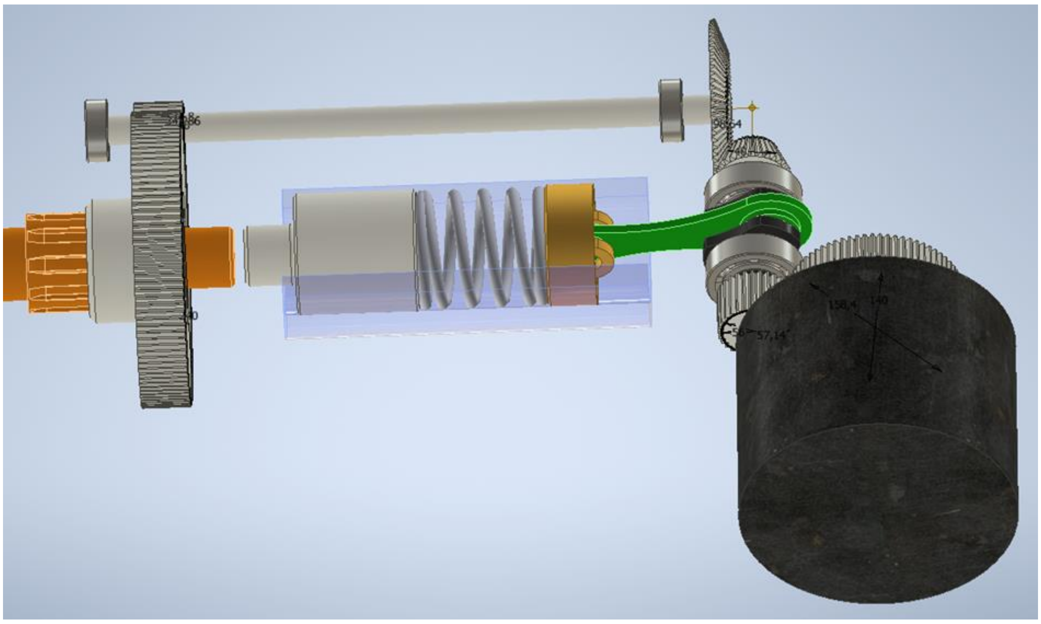

Fig. 7. 3D Model – electric percussion drilling machine with a crankshaft f = 60 Hz

Motors of different power were simulated. For a 30 kW motor (parameters as before), in stable operation the torque demand was N = 130 Nm ÷ 500 Nm, and the motor operated in the speed range of 1410 rpm ÷ 1475 rpm, which according to the catalogue, was a speed near the operating point. Thus, a 30 kW motor was insufficient for this solution. Only for the 45 kW 225M motor (P = 45 kW, N = 290 Nm, n = 1480 rpm, m = 341 kg) the satisfactory results were obtained. Several simulations were performed for various parameters. The selected data and information is presented below.

Drilling machine parameters for a solution with a crankshaft and a 45 kW motor (Fig. 8):

- multiplier from 1480 rpm to 3627.45 rpm – approx. i=0.408 -> f = 60.45 Hz,
- reducer from 3627.45 rpm to 1470.98 rpm – approx. i=2.466,
- reducer from 1470.98 rpm to 245.16 rpm – approx. i=6,
- nominal tool rotation speed n = 245 rpm,
- torque from cutting N = 290 * 0.408 * 2.466 * 6 = 1750.66 Nm,
- impact frequency f = 60 Hz,
- impact piston weight 6.8 kg,
- maximum linear speed of the beater 11.5 m/s,
- calculated impact energy: 450 J.

In steady operation, the torque demand was N = 247 Nm ÷ 268 Nm, and the motor operated in the speed range of 1450 rpm ÷ 1481 rpm, which is the operating point according to its catalogue. The dynamics of the torque change results from the motor characteristics. The selection of the elasticity coefficient and damping of the air cushion are crucial for the speed of the impact piston at the moment of impact, thus it was possible to reduce the piston stroke to 36 mm.

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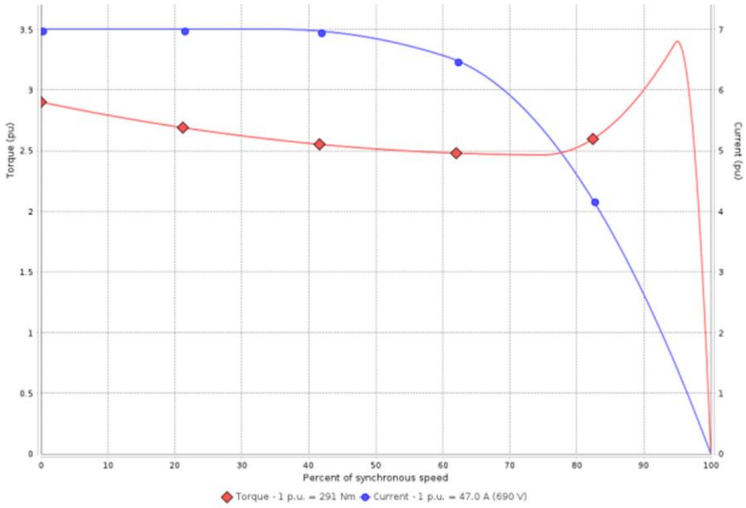

Performance	: 400/690 V 50 Hz 4P		
Rated current	: 81.1/47.0 A	Moment of inertia (J)	: 0.6143 kgm²
LRC	: 7.0	Duty cycle	: S1
Rated torque	: 291 Nm	Insulation class	: F
Locked rotor torque	: 290 %	Service factor	: 1.00
Breakdown torque	: 340 %	Temperature rise	: 80 K
Rated speed	: 1480 rpm	Design	: N

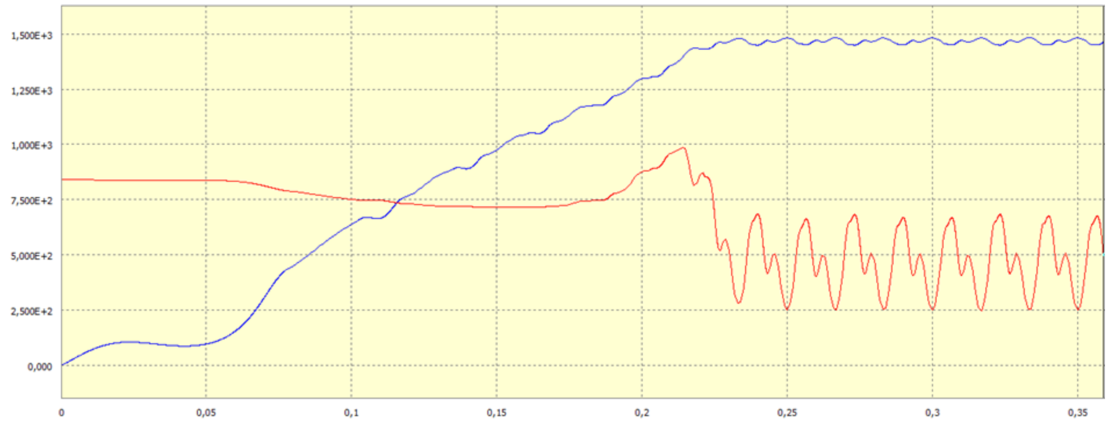

Fig. 8. Characteristics of the 45 kW 225M motor and the speed and torque waveforms for the crankshaft drill

4.4. Drilling machine with a crankshaft – motor with permanent magnets

In the next stage, the target drilling machine with a crankshaft was simulated, assuming the use of an electric motor with permanent magnets. According to the results of previous tests, the crankshaft drilling machine required a motor with a rated torque of 280 Nm. The simulations involved the use of a synchronous reluctance electric motor with permanent magnets from Nidec Leroy-Somer from the DYNEO+ series and Danfoss motors. The tests were carried out for motors with a rotation speed of approximately 1,500 rpm and approximately 3,000 rpm.

Several dozen simulations were performed for various motors and various parameters. The Danfoss EM-PMI300-T310-3200 motor had a power of 94 kW and a torque of 279 Nm at a speed of 3200 rpm and weighted 125 kg. For such a motor, it is possible to directly drive the impact mechanism through the motor, but then it is necessary to use a gear that reduces the revolutions from 3000 rpm to 250 rpm on the tool, so in total a gear or two gears must have a gear ratio of i = 12. Drilling machine operates at a rotation speed of approximately 3000 rpm after approximately 0.7 s. In steady-state operation, such a motor operates correctly already for a torque of approximately 95 Nm, thus use of a smaller motor

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may be considered. Use of permanent magnet motors, despite reduced weight and size, significantly improve the operating dynamics of the drilling machine. Induction motors, due to their very steep torque curve vs. speed characteristics, introduced torque fluctuations. However, the flat characteristics of permanent magnet synchronous motors make it easier to maintain constant torque at variable rotation speed.

5. Conclusions

As part of this research work many tests were conducted to determine possibility of designing an electric rotary-percussion drilling machine with parameters similar to drilling machines currently used on Face Master drilling jumbos. Known solutions for electric drilling machines were analysed. The solutions found in patents, mining models used historically and the solutions used in the construction industry were analysed. Currently, the authors know only one model of a mining electric rotary-percussion drilling machine - Hilti TE MD20. Then, several dozen dynamic simulations of various drilling machines solutions were carried out changing the parameters of the drilling machines and the electric motor.

Currently available linear motors do not allow designing the drilling machines with the expected parameters (especially impact energy and frequency). The solution with a shaft with an inclined disc, although used in the construction industry, is structurally complex, which will most likely not allow for long-term reliability. The crankshaft solution is known from mine electric drilling machines used several decades ago, it is used in drilling machines and construction hammers, and was used in the Hilti mining drilling machine, thus it was considered the most promising solution.

Requirements regarding the impact energy and frequency (450 J, 60 Hz), rotation speed and torque (250 rpm, 800 Nm) require the use of a 30 kW or 45 kW motor. Simulations were conducted for the most advantageous variant, ignoring the resistance to movement and friction, and only asynchronous motors were analysed. Structurally, such a drilling machine must have at least three single-stage gears, one of which is angular. Taking into account the relatively high power and the high degree of complexity of the design as well as the uncertainty of obtaining the required operating parameters of the drilling machine, it is recommended to work first on a solution with a power of several kilowatts. For the purposes of designing a new electric drilling machine, it is necessary to develop a stand for measuring the parameters of such drilling machines, especially for measuring the impact energy and frequency.

Simulations and analyses of drilling machines powered by synchronous motors with permanent magnets showed that this solution has a significant advantage over induction motors. Use of the permanent magnet motors significantly improves the operating dynamics of the drilling machine. Flat characteristics of permanent magnet synchronous motors make it easier to maintain constant torque at variable rotation speed. Danfoss motors selected for simulation can be successfully used from the point of view of torque demand. The best results gave Danfoss EM-PMI300-T310 motors in two versions: with a nominal speed of 1,600 rpm and a power of 59 kW and with a nominal speed of 3,200 rpm and a power of 94 kW. The 1600 rpm motor enables driving the drilling machine using a multiplier to obtain an impact frequency of 60 Hz. However, the 3200 rpm motor (controlled in such a way to obtain a rotation speed of 3000 rpm) enables direct driving the impact mechanism with a frequency of 60 Hz. It should be noted that both motors have higher torque than required. In particular, the 3200 rpm motor with a nominal torque of 279 Nm has a significant torque reserve, compared to the required 95 Nm during stable operation of a drilling machine. A drilling machine with a Danfoss EM-PMI300-T310 motor arranged longitudinally has dimensions similar to those of hydraulic drilling machines (Fig. 9), so the use of a smaller motor will be more advantageous in terms of weight and size.

The Danfoss motors have very high power and there is a need for their proper control and cooling. When using a higher speed motor, consider selecting a smaller motor, such as the EM-PME375-T150-2600, which has a nominal speed of 2,600 rpm but can operate up to 4,000 rpm. At a speed of 2,600 rpm, it generates a torque of 147 Nm with a power of 40 kW and it weighs 75 kg.

Testing the electric drilling machine with a power of several kilowatts enables determining the real operating parameters and eliminate defects typical for the prototype, before designing the drilling machine for the drilling jumbos. Additionally, this solution will allow for verification and validation of digital models, what will facilitate designing the more powerful drilling machine.

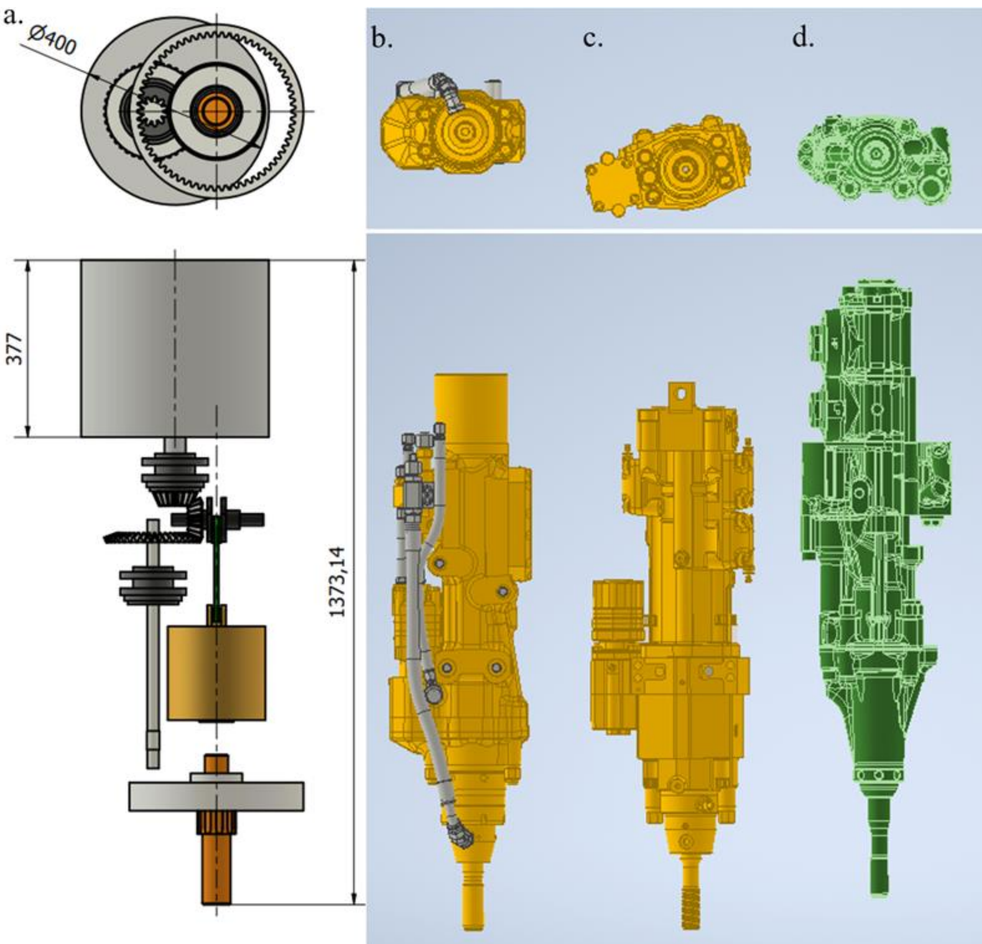

Fig. 9. Comparison of drilling machines:

a. electric with Danfoss EM-PMI300-T310 motor, b. hydraulic HC95, c. hydraulic MM20, d. hydraulic HC109

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Peaking water power plant powered by mine water

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Abstract:

A water power plant in a mine is an innovative solution that can use rainwater, underground and industrial water collected in mines to produce electricity. The process involves pumping water to a higher level and then draining it down, which drives turbines that generate electricity. Another solution may be to direct the water from higher levels to lower levels to the turbine blades. This approach allows for the effective use of existing mine infrastructure, contributing to sustainable development and reducing greenhouse gas emissions. Additionally, it helps manage mine water, offering a stable source of energy for local communities and industry. Examples of operating water power plants in mines around the world confirm their effectiveness and economic benefits, indicating the potential of this solution in green energy.

Legal requirements related to using the energy of a water stream in a technical device (generator) in a mining plant, an overview of existing solutions and an original concept of a water power plant with a tubular vertical shaft are presented.

Keywords: water power plant, underground mine, hydro-generator, water power plant with a tubular vertical shaft

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1. Introduction

As a result of the energy crisis in 1973, most developed countries took actions whose main goal - among other things - was to create new sources of electricity not based on fuels (especially liquid fuels), but using the renewable energy. Among these new sought sources, hydropower has come to the fore. Therefore, small power plants and water power plants that had been shut down in previous years aroused great interest. This was due to very low oil and gas prices, which led to a lack of competition with high-capacity power plants using fossil fuels. Interest in the possibility of using existing water dam structures for energy purposes for various water and economic purposes has resulted in the intensive development of small hydroelectric power plants, which include hydroelectric power plants with a capacity of approximately 5 MW, and in some countries even up to 10 MW [1].

In addition to using water in the above-mentioned structures, research work has begun on the development of using the subsurface water as a source of energy. This mainly concerns mine water, the energy associated with its flow can be used to produce electricity [2]. Systems producing electricity from mine water have been created, but for many reasons (including economic ones) they have not been widely implemented so far. It was only at the end of 2023 that a power generator was launched in the liquidated Boże Dary mine in Katowice [3]. The system uses the energy of water dropped from a level of 183 m to a level of 416 m. This water drives a hydro-generator located at the 416 m level. The produced electricity is directed to the network used by the mine's pumping station.

Another solution may be a power plant generating electricity during peak or emergency demand, closely linked to the operation of the main drainage installation for underground workings of deep mines. Very large amount of seam and technological water is pumped out of mine underground. On the surface, this water has high potential energy relative to the underground reservoirs from which they are pumped off. During peak hours or in emergency situations, this enables using this energy for production of electricity using a water power plant. The key issue of the solution is to supply the power plant turbine with water from the main discharge pipeline, i.e. contaminated water, as well as to use a special solution for the vertical tubular shaft bearing and effective lubrication and cooling of the main components of the power plant. This will enable obtaining higher specific power, high durability and quiet operation of the power plant. The vertical layout of the power plant covers much less space in the limited underground infrastructure of mines.

The power plant can be activated in a very short time, which is particularly important in emergency and crisis situations. It also has a high level of resistance to natural disasters, terrorist attacks and warfare.

2. Legal regulations and associated documents

Use of the energy of a water stream in a technical device (generator) in a mining plant requires compliance with the following legal acts:

- Act of June 9, 2011 - Mining and Geological Law, which specifies the principles and conditions for undertaking, performing and terminating activities in the field of: geological works, extraction of minerals from deposits, underground non-tank storage of substances, underground storage of waste [4].
- Regulation of the Minister of Energy of November 23, 2016 on detailed requirements for the operation of underground mining plants [5].

Art. 2, Item 1 of the Act [4] says, among other things, that the provisions of the above-mentioned the Act, with the exception of Chapter III of the Act (dedicated to concessions), shall apply accordingly to the following:

1. construction, expansion and maintenance of drainage systems for closed mining plants;
2. work in the workings of liquidated underground mining plants, listed in the regulations issued on the basis of section 2, for purposes other than those specified in the Act, in particular tourism, medical and recreational purposes;

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3. underground work for scientific, testing, and training activities for the purposes of geology and mining;
4. tunnel drilling using mining techniques;
5. liquidation of facilities, equipment and installations referred to in Items 1- 4.

Additionally, the provisions of the Act of July 20, 2017 - Water Law [6] should be taken into account, where in Section I, Chapter I, Art. 7, Item 1, point 3 there is a provision stating that the Act do not apply to the introduction of water into the rock mass from the drainage of mining plants and the use of water referred to in Item 2. point 2, in turn, states that the provisions of the Act do not apply to the use of water collected using devices and technical installations that are not water devices. According to the definition available on the website of the State Water Holding Wody Polskie [7], it can be read that water facilities construction of which requires a water permit include the following:

- damming, flood protection and regulation devices or structures, as well as canals and ditches,
- artificial reservoirs located on flowing waters and facilities related to these reservoirs,
- ponds - in particular fish ponds and ponds intended for sewage treatment or recreation (excluding ponds that are not filled as water services, but only with rainwater or meltwater, or groundwater of an area not exceeding 5,000 m^2 and a depth not exceeding 3 m from the natural land surface, with the scope of impact not exceeding the boundaries of the area the plant owns, or the area within the area of impact, if the plant has the prior written consent of the owners of the land affected by the impact to construct a pond - these require a water law notification,
- facilities for capturing surface water and groundwater,
- hydropower facilities,
- outlets of sewage devices used to introduce sewage into water, land or water facilities and outlets used to introduce water into water, land or water facilities,
- permanent devices used for catching fish or obtaining other aquatic organisms,
- devices for breeding fish or other aquatic organisms in surface waters,
- retaining walls, boulevards, quays, piers, piers and marinas,
- permanent devices used for inter-coastal transport.

Please remember that other devices or structures used to shape water resources or use these resources may also be classified as water facilities.

3. Samples of the existing solutions

There are well-known examples of energy recovery from falling water, in particular the so-called Small Hydroelectric Power Plants (SHPP), based on hydro-generator sets, consisting of an electric generator driven by a turbine, which in turn is powered by a water stream [8].

According to the report [9], at the end of June 2021, 775 SHPPs were operating in Poland. The total capacity of such installations was 296 MW.

The only known concept of a solution similar to the one described in this article is the plan to use the workings of the Prosper-Haniel mine in Bottrop as a pumped-storage power plant. Information about this comes from publications 2017-2018 [10, 11, 12, 13, 14]. However, information published in the cited references is a description of a concept that has not been finalized yet. Nevertheless, post-mining areas are gradually revitalized [15].

Literature items containing the results of test in Serbia, Turkey, Norway [9, 16, 17] clearly indicate that facilities such as SHPP, despite their relatively small scale (installed power, extensive area related to the facility's infrastructure, etc.), may have a significant negative impact on environment. It depends on the extent to which the negative impact of SHPP facility on environment and the method for reducing this impact were taken into account, already at the designing stage. It should be borne in mind that the term "small" in the definition of an SHPP facility refers mainly to the turbine power, and not to the size of the accompanying hydrotechnical facilities (e.g. dam) [18, 19]

There are the following advantages of SHPP:

- improving the runoff coefficient, especially on smaller rivers,
- potential retention and flood protection function resulting from water damming,
- clean and waste-free energy production.

The limitations indicated above (potential negative impact of SHPP infrastructure on the environment) do not apply to the concept described in this article, because the suggested approach does not require constructing the hydrotechnical facilities on the surface. The existing conditions are used, and technical work is related to possible adjustment of the water intake, installation of the hydro-generator unit in a selected location and introduction of necessary changes in the construction of pipelines [20, 21, 22].

This is also the main advantage of the suggested solution - no harmful impact on the environment, while at the same time utilizing the energy of the water stream by transforming it into electricity. Additionally, the experience gained will enable proposing the improved SHPP technology, adapted to the hydrological conditions of the mine, which, on a scale related to the number of available shafts, may provide measurable benefits regarding the amount of energy produced.

A disadvantage may be the relatively low power of the generator in relation to the power of equipment existing in the mine. For example, the estimated power of the generator is approximately 200 kW, with the demand of the main drainage pumps ranging from several to tens MW.

Activities related to the liquidation of mines (including KWK Boże Dary mine), as well as post-liquidation procedures, are energy demanding. An example are pumping stations, which still have to pump water after the mine is closed. This requires electricity, most of which comes from burning fossil fuels. This forced to take a number of actions aimed at reducing the demand for the so-called "grey energy" produced from fossil fuels by introducing pro-ecological solutions.

The project related to the production of electricity in the mine assumed the following three main assumptions:

- use of water energy,
- reducing the demand for electricity,
- implementation of innovative solutions in the mining industry.

The above assumptions were the reason for launching the hydro-generator in the pumping station in Boże Dary mine. This is the first solution of this type in the European mining industry. The hydrogenerator was built at a level of 416 m in a former underground mining plant. It allows the production of clean electricity using the energy of water dropped from a level of 183 m to a level of 416 m.

It must be remembered that water must be constantly pumped out of closed mines and the pumps need energy to operate. Moreover, energy is necessary for operation of fans, control and measuring equipment, operation of the hoisting machine and lighting. Installing the water system ensuring the water flow through the hydro generator (Fig. 1) will enable producing electricity, which will then be consumed in the pumping station. It is estimated that the average annual electricity production in this case will amount to just under 1,600,000 kWh. Such action will significantly reduce the cost of purchasing electricity and its distribution services. Taking into account the current market situation regarding the electricity price, we can count on a quick payback. Payback time is estimated at a maximum of 2.5 years. It should be emphasized once again that all electricity will be consumed at the point of production and is not expected to be directed to the local operator's distribution network.

Fig. 1. Hydro-generator installed in the Boże Dary mine [23]

Mining plants have many hydraulic installations that can potentially be used to produce electricity. The conditions for using water energy are the following:

- enough height of water fall,
- local technical capabilities.

Potential places for using the water turbines in mines are the following:

- gravity water discharge from not deep levels,
- water outflow from the main drainage pipelines when pumping from deeper to shallower levels,
- water flow from the main drainage pipelines on the surface,
- cascade flows of mine water in the beds of under surface streams.

Depending on the choice of location, various designs of water turbines can be used [24, 25, 26]. Examples of design diagrams are shown in the below figures (Fig. 2 to Fig. 5).

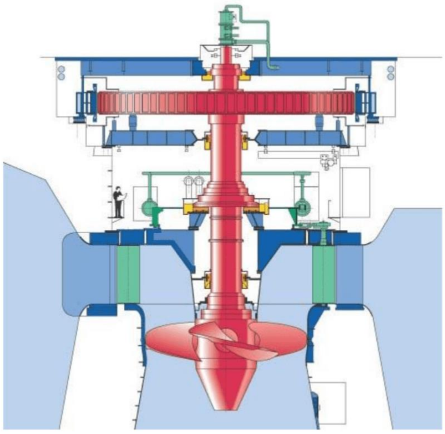

Fig. 2. Schematic diagram of Kaplan turbine [27]

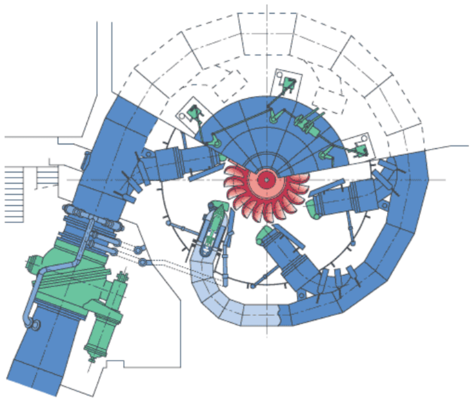

Fig. 3. Schematic diagram Pelton turbine [28]

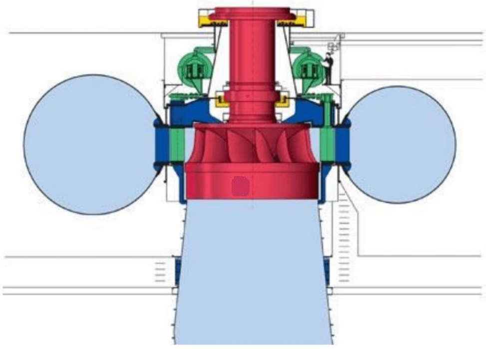

Fig. 4. Schematic diagram of Francis turbine [29]

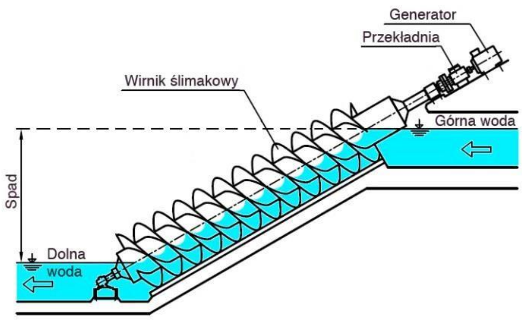

Fig. 5. Schematic diagram of Archimedes turbine [30]

Installation of a hydro-generator in the Boże Dary mine pumping station (Fig. 1) is the first pilot project of such type. Electricity savings were observed after just a few days of operation of this unit. This clearly indicates that further investments of this type are absolutely justified. Taking into account stable operating conditions, due diligence of the properly trained staff and regular inspections and services, the device will operate without failure for at least a dozen or so years [31, 32, 33, 34, 35, 36, 37].

Currently, similar projects are planned to be implemented in the branches of KWK Centrum mine and KWK Pokój I - Pokój II mines. Additionally, it is possible to install lower-power hydro-generators at pumping stations on discharge collectors (the average power of one collector is from 30 to 40 kW).

The CZOK branch currently has 16 pumping stations, and soon there will be 18 of them. Therefore, there is great potential to implement further innovative projects of this type, which will bring significant savings.

4. KOMAG solution

At KOMAG, in cooperation with specialists from the Silesian University of Technology, conceptual work has been started several years ago on one of the solutions for a power plant with a vertical axis of rotation. Fig. 6 (half-cross-section) shows a water power plant according to the idea of the author's team.

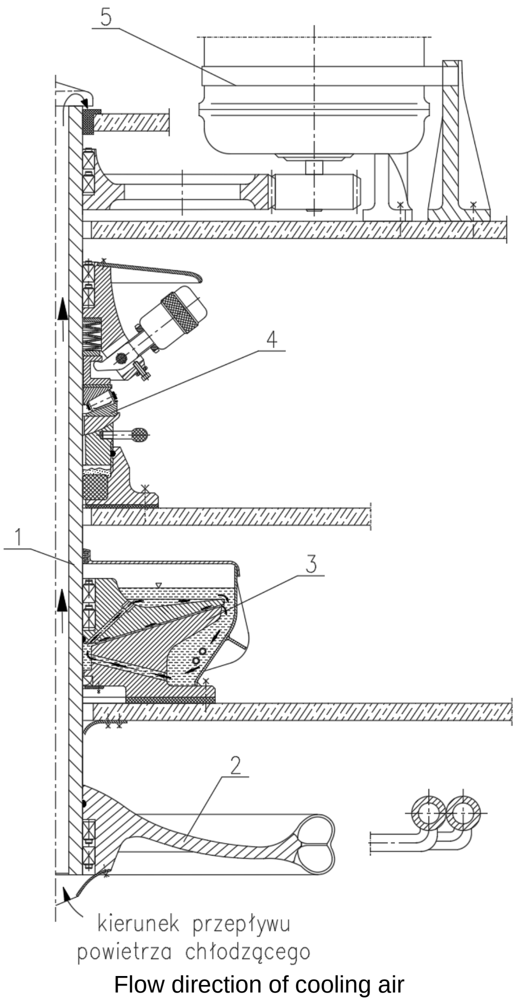

Fig. 6. Water power plant according to the idea of the author's team [38]:
1 - tubular shaft, 2 - Pelton turbine rotor, 3 - main longitudinal-transverse plain bearing with hydrodynamic lubrication, 4 - rolling bearing supporting the start with an automatic load switching system, 5 - electric generator with auxiliary devices

Bearing of machine shafts with a vertical axis of rotation in machine construction often poses a number of specific design and operational problems. They result from the fact that the loads, especially longitudinal ones, on such shafts during the start-up phase are generally significant, and their rotational speed is most often variable in a wide range. There are often a number of additional requirements, such as the need to reduce noise or reduce resistance during rotation [39].

Shafts of hydroelectric power plants, especially of the dam type, most often operating continuously, are equipped with Kingsbury-Michel type segmental plain bearings with swingingly supported segments as ring sections. Such bearings operate quite well under hydrodynamic lubrication at nominal rotational speed, but are sensitive to large changes in sliding speed during bearing start-up and run. These structures are highly complex, expensive and require special cooling of lubricating oil systems, what significantly reduces the overall energy efficiency of the power plant. During the start-up phase, which must take place under full longitudinal load, such bearings are usually additionally lubricated hydrostatically, what additionally requires using the special, high-pressure lubricating oil pumps and proper automatic system for switching the operation of the lubrication and oil cooling system. The same difficulties occur during bearing overrun when the motor is stopped. Such solutions are unsuitable in a situation where the start-up, and therefore the run of the power plant must take place with increased frequency, as is the case of peaking power plant according to the concept presented in the article.

In the solution for the vertical shaft bearing of the discussed water power plant powered by the drainage system of a deep mine, it was suggested to use a special hybrid bearing, which in the range of nominal rotation speed transfers the longitudinal and transverse load through a plain bearing with liquid lubrication, and during the start-up and overrun, this bearing is supported by additional rolling bearing, automatically disconnected after the motor shaft reaches the set rotation speed, what allows for the hydrodynamic lubrication in the plain bearing.

When sliding of the journal on the bearing shell is sufficient, the load is switched between both types of bearings automatically at the set rotation speed.

As part of the conceptual work, two variants of the plain bearing were suggested. The first one is a longitudinal-transverse bearing lubricated with oil in a closed circuit. In the second variant, it is suggested to use high-pressure water in the mine's main drainage pipeline, which, after proper separation of impurities, lubricates the plain bearing, thus creating a system with basic hydrostatic lubrication, additionally supported by the hydrodynamic lubrication. Water as a lubricating and cooling medium in this variant works in an open system, i.e. after passing through the sliding bearing, it is discharged into the lower mine water tank, transporting the heat generated in the bearing. In both variants, the longitudinal bearing load Q consists of the sum of the weights of all components installed on the shaft and the weight of the shaft itself.

Lubrication grooves are made on the sliding surface of the journal. These grooves make lubricating wedges with high load-bearing capacity, forming when the journal slides on the bearing. In this way, nature of operation of the suggested plain bearing is similar to that of the Kingsbury-Michell type bearing, ensuring its very high load-bearing capacity.

The lubrication grooves additionally act as blades of a centrifugal pump, causing intensive circulation of the lubricant, shown as arrows in Fig. 7, to effectively remove the heat generated in the bearing slip zone, regardless of whether it is lubricated with oil or water.

In the variant of the bearing with oil lubrication, the lubricant returns to the bearing entrance after cooling, what is additionally facilitated by the gravitational forces caused by the change in oil density as a result of the temperature difference. If necessary, the oil cooling system can be equipped with an internal coil through which part of the water supplying the power plant or water from the mine's fire protection system flows for sufficient oil cooling.

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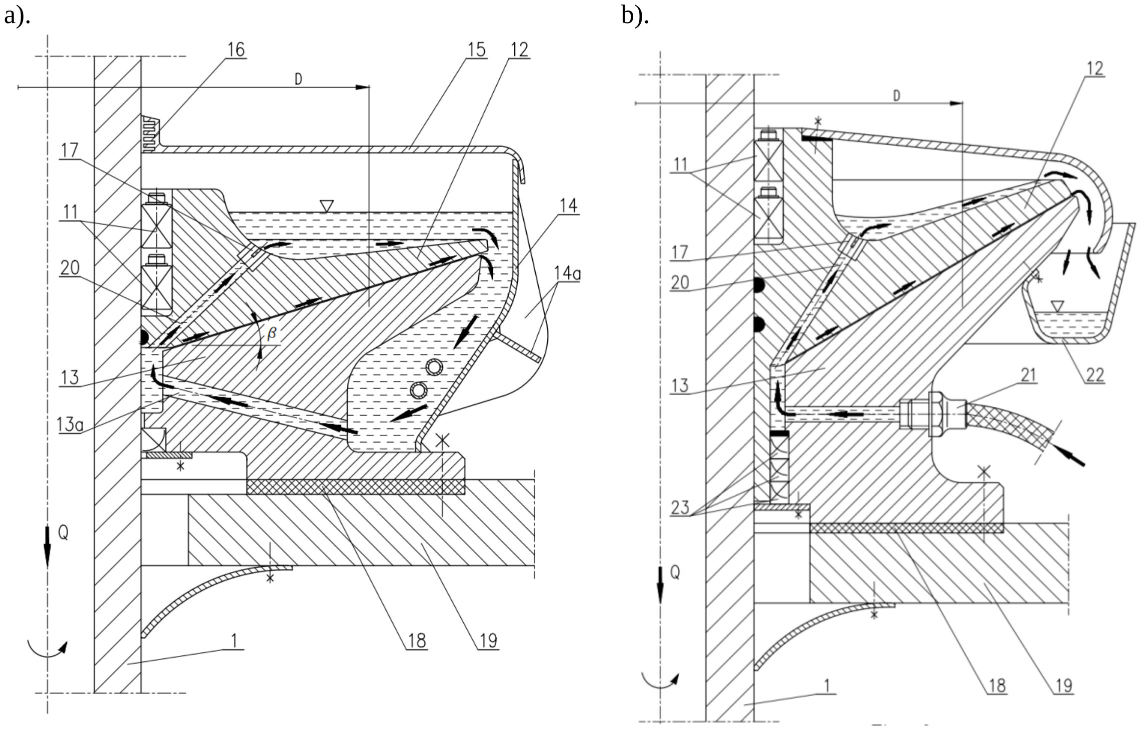

Fig. 7. Main longitudinal-transverse plain bearing with hydrodynamic lubrication in two lubrication variants [38]: a) oil lubrication, b) high pressure water lubrication

Optionally, additional inclined holes can be made in the journal, ending with adjustable nozzles through which part of the lubricating liquid flows onto the upper surface of the journal, enhancing its cooling.

In addition to transferring the main longitudinal load Q, both variants of the plain bearing also transfer transverse forces that may occur during operation of the power plant bearing system. In the case of a tapered journal, the amount of lateral force that the plain bearing can transfer depends on the "beta" cone angle. The large average diameter D of the bearing sliding surface allows for high load-bearing capacity because the average contact pressures decrease and the average sliding speed in the bearing increases. This enables obtaining the hydrodynamic lubrication at a significantly reduced rotation speed of the motor shaft, which is very desirable in the suggested solution. The polymer underlay (18) dampens vibrations and noise.

High water pressure in the drainage pipeline from which the power plant is supplied leads to the suggestion of using the water as a lubricant. The unfavourable property of water in relation to oil in the form of low water viscosity can be compensated by its high pressure, what allows obtaining an additional hydrostatic lubrication in addition to the hydrodynamic lubrication described earlier.

Fig. 7 b) illustrates a variant of a plain bearing in which water for lubrication and cooling of the bearing is supplied through connection (21) attached to the bushing (13). Water from the drainage pipeline should be pre-cleaned to remove mechanical impurities, while typical chemical impurities in mine water are not important with appropriate anti-corrosion protection of the components. After flowing through the bearing, the water flows into the surrounding gutter (22), from where it is directed to the lower tank together with the water that flows through the turbine rotor. The high-water pressure zone in the bearing is sealed against the moving part of the journal with a multi-stage lip seal.

Regardless of the plain bearing variant in the presented water power plant concept, it operates only when there is liquid lubrication system. During start-up and during run, when the sliding speed does not allow obtaining the effect of liquid lubrication, it is suggested to use a special system that relieves

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the plain bearing and protects against operation in semi-dry friction conditions, which may lead to rapid increase in abrasive wear of the journal and bushings, with the risk of seizure symptoms. High resistance to movement when liquid lubrication is not guaranteed is also very unfavourable. The system that relieves the load on the plain bearing during start-up and run uses a supporting rolling bearing that is switched on automatically. This system is illustrated in Fig. 8.

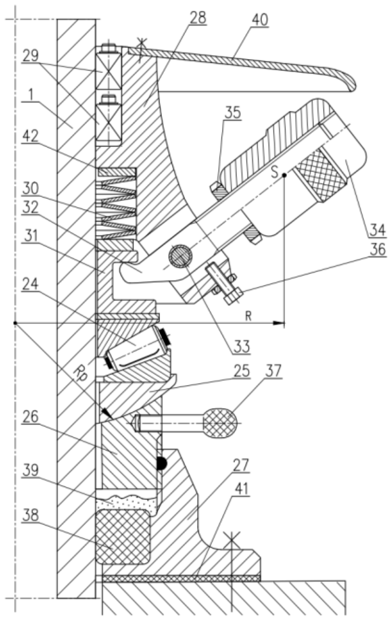

Fig. 8. System that relieves the plain bearing [38]

The system works as follows. During standstill and start-up, full load on the shaft (item 1 in Fig. 6) is transferred by the supporting rolling bearing (24), which reduces starting resistance. It is preferable to use a tapered roller bearing, capable of transferring the significant longitudinal and transverse loads. The bearing (24) supporting the start-up is based on a spherical support (25) alleviates uneven stress distribution resulting, for example, from manufacture deviations of the components.

When the shaft rotation speed increases after starting the power plant, the inertial-lever mechanism begins to operate (upper part Fig. 6). Articulating levers (32) mounted on pins (33) increase pressure on the sliding sleeve (31), which additionally bends the disc spring 30. This gradually relieves the load to the supporting rolling bearing (24), while simultaneously switching the load to the plain bearing, where the conditions for hydrodynamic lubrication are gradually created. The magnitude of the force bending the disc spring at a given rotation speed of the system depends on the mass of the inertial weights (34) and the radius R of the position of their centre of mass S. Position of the weights is adjusted by turning the weights on the fine thread of the articulating levers. After final settlement, position of the weights is locked with locknuts. It is planned to use three levers, evenly distributed around the circumference. At the assumed nominal shaft rotation speed, the load is fully switched to the main plain bearing, and the rolling bearing supporting the start-up stops, waiting for starting the run.

During run, when the rotation speed decreases, the load switching system operates in a reverse direction, gradually transferring the load to the rolling bearing, which transfers the load, until the shaft stops. In this position, the supporting bearing remains ready for restarting. In the extreme position, the articulating levers rest on adjustment screws with locknuts. This eliminates the possibility of vibrations in the system, which may arise, for example, due to manufacture deviations in the components.

5. Control of the components of the peak power plant supplied with mine water

The design and principle of operation of the discussed power plant is such that, apart from the electrical systems, the control of which will be omitted in this research work, the power plant does not require any special control, apart from the bearing system of the vertical shaft of the power plant.

After assembling the power plant, careful adjustment is required to determine the most favourable shaft rotation speed at which the load, described in the previous chapter, is switched from the rolling bearing supporting the start-up and run to the main bearing of the power plant, which is a plain longitudinal-transverse bearing with hydrodynamic lubrication. The lack of significant hysteresis in the switching system means that the rotation speed at which switching should be for both switching directions is practically the same. This rotation speed should be determined through operational tests at the lowest possible level so that the load switching takes place smoothly, without any significant disturbances or acceleration in the shaft rotation. This determination should be made by rotating all inertial weights in the same way at a standstill, thus changing the rotation radius R equally for all the weights. A favourable condition for the operation of a plain bearing, regardless of whether it is an oil- or water-lubricated variant, is a possibly constant temperature at the installation site of the power plant, what means that there is no significant impact of the ambient temperature on the change in the viscosity of the lubricant. However, it should be periodically checked for changes that may cause the above-mentioned undesirable phenomena during switching, e.g. caused by wear of system components.

Mechanism for positioning the supporting rolling bearing requires particularly careful, one-time adjustment (Fig. 8, item 24). This adjustment should be made before determining the optimal rotation speed at which the load is switched, as described above. The above-mentioned bearing supporting the start-up is loosely mounted on the shaft (1) and rests on a spherical support (25), ensuring even distribution of the load to the rolling components. The spherical support rests on the adjustment sleeve (26), which is connected to the base (27), attached to the ceiling of the chamber in which the power plant is installed.

Rotating the adjustment sleeve serves to precisely position the supporting rolling bearing relative to the load switching mechanism previously described. This adjustment is best performed according to the following procedure (before filling the sliding bearing with oil or with the water supply as a lubricant closed): By turning the adjusting sleeve (26) while standing still, the main sliding bearing should be fully loosened, which will result in great ease of turning the shaft, because then the full the longitudinal load Q will rest only on a rolling bearing with low resistance to movement. Then gradually lower the adjustment sleeve until the journal of the plain bearing comes into contact with the bush. The signal that this condition has been reached will be a sharp increase in the resistance to rotation of the shaft, especially when there is no lubricant in the bearing. Then the adjusting sleeve should be raised again by the determined amount resulting from the structure of the slide bearing relief system. Such a position will be characterized by a large decrease in the resistance to rotation of the shaft, and the disc spring (30) will obtain an initial deflection. In this position, fill the sliding bearing with oil to the appropriate level or open the water supply to act as a lubricant in the case of water lubrication of the bearing.

Correctly performed bearing adjustment is a condition for maintaining a very high operational durability.

6. Conclusions

Cost of electricity is the result of many factors, including production costs, distribution costs, energy policy as well as supply and demand. The introduction of renewable energy sources and technologies that increase energy efficiency can help to stabilize or reduce energy costs in the future.

Water power plant in an underground mine is an innovative solution that uses underground and industrial water present in closed or active mines to produce electricity. Water flowing from a higher to a lower level drives a turbine that generates electricity. The key advantages of this solution are as follows:

- use of existing infrastructure - adaptation of existing systems of workings / tunnels and pumps in mines reduces investment costs,
- sustainable development – the use of a renewable energy source, such as water, supports environmental protection and reduces greenhouse gas emissions,
- water management – water power plants in mines help in managing mine water, if it is only pumped, it can reduce the problem of water drainage and purification,
- effective water management – it can help in the controlled drainage of water to the mine surface, which is beneficial from the point of view of ecology and water management,
- energy stability – provides a stable and reliable source of energy that can support local communities and industry,
- examples of application - in the world, but also in Poland, there are functioning water power plants in underground mines, which prove their effectiveness and profitability.

Water power plants in underground mines offer a sustainable energy solution that not only uses the resources of mines after their operation, but also contribute to development of green energy production and environmental protection. The author's solution with a vertical pipe shaft presented in the article fits very well into the problem of water power plants used in underground mines. It is characterized by particularly high durability of the system bearings. It results from the fact that the main plain bearing operates only under full hydromechanical lubrication, i.e. practically without wear, while the rolling bearing that supports starting and run during braking operates for short time intervals and at reduced rotational speed. For the same reasons, the bearings of the vertical shaft of the power plant emit low noise with low vibration. Low resistance to movement under the nominal rotation speed of the power plant ensures high energy efficiency of the bearing as well as the operational durability of the entire power plant according to the described concept.

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Solid gravity energy storage in mine shafts – feasibility and functionality

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Abstract:

Power and Energy storaging is bacoming as one of contemporary the biggest chalenges. Main reason is development of renewable Energy sources and irregular production cycle. In article is described typology of energy and power storaging solutions and solid gravity energy storage (SGES) place in this typology with briefly description of gravity storages idea. As an industrial proces SGES are analyzed theoretical and practical SGES feasibility. Constraints and functionality of SGES is a background for SGES feasibility analysis in main areas of feasibility (technical, legal, economic and operational). Because expectations for SGES are not definied in article was done analysis for two ways – for existing shaft with equipment and for expected SGES capacity. Results of analysis are presented as final conclusions.

Keywords: energy storaging, solid gravity energy storaging, shaft as a storage, gravity storaging

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1. Introduction

Need for energy storage appeared in the 20th century with the popularization of using the electricity and with growing demand for it. Energy storage means capturing energy produced at a given moment and storing it for later use.

However, only in recent years, due to the growing ecological awareness and the related development of renewable energy sources (RES), there has been a sharp increase in interest in energy storage. Importance of energy storage is indicated by the UN 2030 Agenda for Sustainable Development, which includes affordable and clean energy as the seventh of the 17 Sustainable Development Goals [1].

Emergence of renewable electricity sources in the form of photovoltaic cells and wind generators has revealed a dissonance between the energy generation characteristics of these sources and the energy demand. This results in the loss of electricity already produced and insufficient use of the investment outlays. The idea of storing already generated energy in energy storage facilities has emerged. The idea of storing electrical energy was already known, but as systems stabilizing electrical systems (e.g. in cars with spark ignition combustion engines, now developed into cars with hybrid drives). Pumped-storage hydroelectric power plants have been built in large power systems for many years, the task of which is to stabilize such a system by storing excess energy production and releasing it when there is a shortage of energy in the system.

Many installations, not only industrial ones, are highly sensitive to power failures. In the case of smaller installations, electric generators powered by diesel engines have been successfully used for many years, often to protect only the most sensitive systems to ensure their continuity of operation;

Electricity storage in electric batteries (e.g. cars) has been used for many years as equalizing power supply (short-term) or alternative power supply (e.g. submarines).

Originally, all forms of energy storage (especially pumped-storage power plants) were used as compensation systems to protect industrial installations against power failures in power grids lasting at most a few hours. In this way, the most sensitive installations were protected [2, 3].

Nowadays, among the many possibilities of storing energy and/or power, there are also installations using potential energy, i.e. the phenomenon of gravity, including energy storage facilities using the water gravity in deep mine shafts. This article is devoted to the analysis of the last one.

2. Typology of energy or power storages in the light of current ideas

In Fig.1 current typology of energy storage developed in China is presented [4].

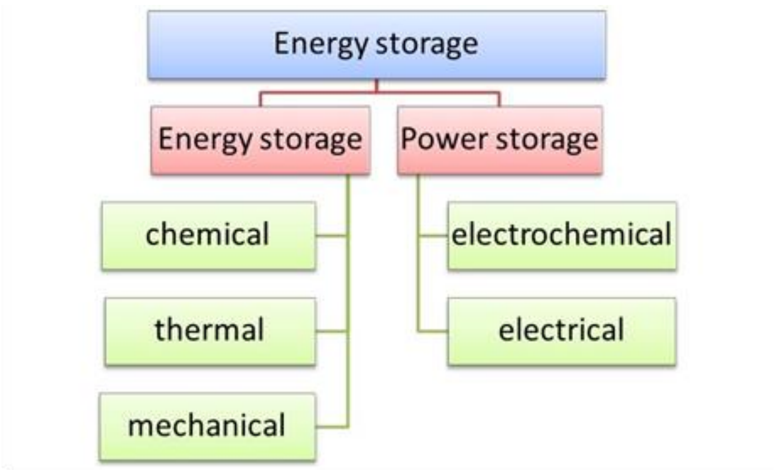

Fig. 1. General typology of energy storage [4]

Due to the thematic scope, energy storage systems using mechanical energy require a more detailed classification, which is shown in Fig. 2.

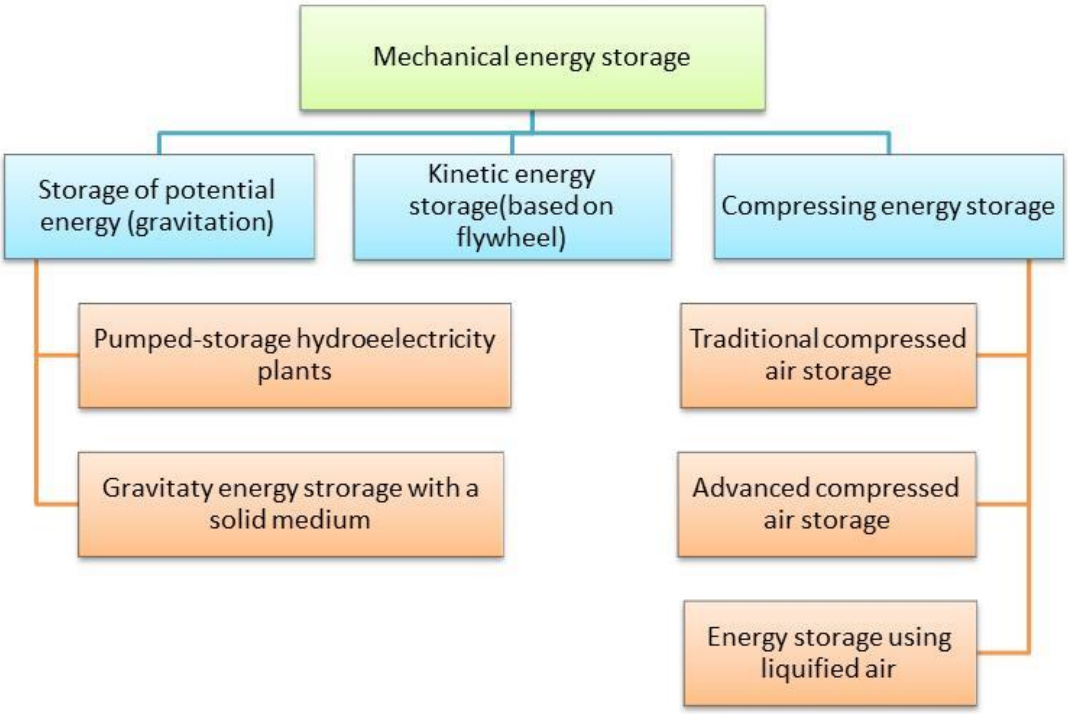

Fig. 2. Typology mechanical energy storage [4]

Pumped-storage hydroelectricity power plants have been built in large power systems for many years, the task of which is to stabilize such a system by storing excess energy and releasing it when there is a shortage of energy in the system. However, this solution has a significant drawback in the form of a high necessary difference in levels for the lower and upper water reservoirs and significant space requirements to obtain a enough capacity to store energy. Pumped-storage hydropower plants currently existing in Poland have an energy storage capacity of approximately 8 GWh, and the possibility of increasing this capacity is estimated to be several times greater at best. After lignite mining in the Turów open-pit mine ended, it is suggested to build a pumped-storage power plant in about 30 years with a capacity of 2,300 MW and a storage capacity of up to 160 GWh, which is relatively small [5]. Since the 1960s, the idea of using the liquidated underground mines as pumped-storage power plants, i.e. energy storage, still returns, but it has not been widespread so far.

Since around 2015, gravity storage of electricity has been replaced more and more often. A gravity storage is a type of electrical storage device that stores the energy accumulated in an object resulting from the change in height increasing its potential energy. Gravity storage works by using excess energy from the grid to lift mass to increase potential energy, which is then dropped down to convert the potential energy into electrical energy through an electric generator [5]. Many technology demonstrators were created in a form of towers with weights lifted in various systems.

It was only in 2023 that the first commercial surface gravity energy storage facility was launched in China (Fig. 3). The surface gravitational energy storage facility launched in the city of Rudong in China's Jiangsu province has a capacity of 100 MWh with a power of 25 MW. The general idea of this storehouse is to locate multiple loads next to each other in one building. Storing energy means lifting these weights, and releasing energy means lowering them. This ensures continuous operation of the storehouse compared to a single weight one and extends time of energy release [6].

Fig. 3. Energy storage system in, China under construction [*Image: Energy Vault, Business Wire*]

In 2017, the concept of using the mine shafts for energy storage was presented. The main argument for this solution is the significant depth of many shafts - greater than height of the structures on surface. In the case of liquidated underground mines, it is possible to use part of the remaining mine infrastructure, including hoisting machines (shaft hoist system) and the mine's power system. The social aspect of such an idea is also pointed out, in the form of preserving a certain number of jobs for people whose competences are difficult to use in other professions. For this reason, various concepts of underground gravity energy storage in mine shafts have been presented in recent years. Polish underground coal mining industry, whose mines had over 130 shafts at the end of 2023, according to some opinions, could become a potential energy storage complex. However, it should be noted that to date, no gravity energy storage in a mine shaft has been launched anywhere, not even in the form of an underground demonstrator. Various technical concepts of energy storage in mine shafts are presented, including those based on the idea of lowering and lifting large homogeneous masses or large groups of smaller weights or containers (with water or solid bulk materials).

3. Constraints, feasibility and functionality of solid gravity storage in abandoned mine shaft

For each technical solution, there are constrains resulting from various conditions, which translate into real constrains that determine the practical feasibility of the solution. The ideas for gravity energy storage in mine shafts presented in [2, 3, 4, 7, 8] do not analyse the environment, surroundings and constrains for the energy storage process, which in practice may translate into the feasibility of implementing the project. The existing constrains are, in practice, a consequence of environment in which the project is implemented by its close surroundings, which impose significant constrains (Fig. 4).

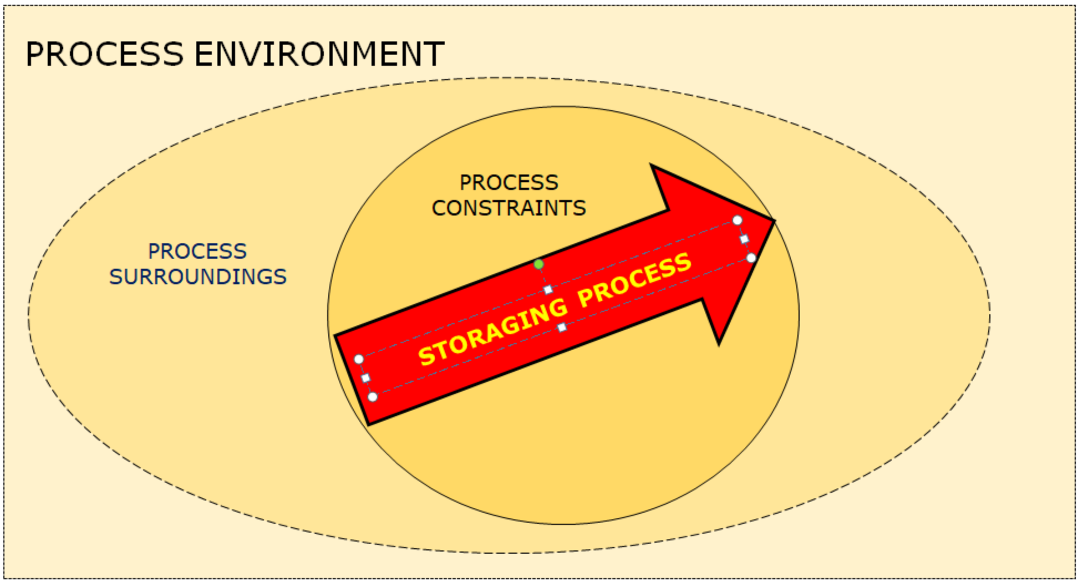

Fig. 4. Environment surroundings and constraints for the technical process [source: Author's]

Taking into account constraints in the designing process is necessary because it determines the possibility of implementing the planned project, i.e. in this case, a gravity energy storage facility in an underground mine shaft. It is indicated [8] that there are two levels of feasibility:

- Theoretical (dispositional) feasibility means that the intended project is consistent with the laws of nature (e.g. the laws of physics, mechanics, thermodynamics, etc.).
- Practical (situational) feasibility means that the intended project (object, process) can be implemented in specific conditions (including place and time).

The practical project feasibility, which should be separated from theoretical feasibility (Fig. 5), is an important issue.

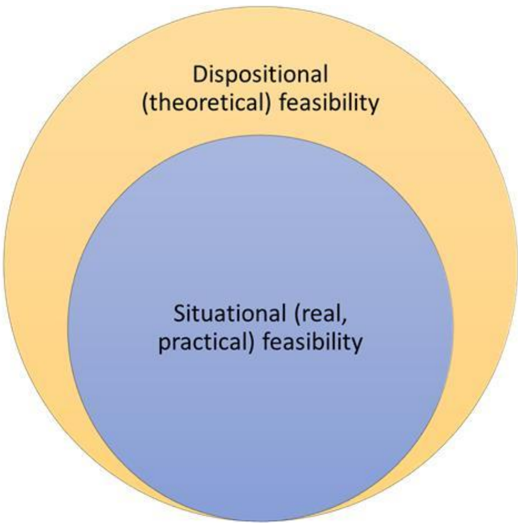

Fig. 5. Theoretical and practical feasibility [9]

Undertaking projects that are practically (situationally) impossible does not lead to achieving the intended goal, but generates costs and losses.

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The basic areas of assessing the feasibility of a project involving the creation of a gravity energy storage facility are shown in Fig. 6:

- **Technical feasibility**. This is an assessment that focuses on the technical resources available to implement the project. It should be noted that in practice, resources in the sense of the socio-technical system should be considered, i.e. not only material resources, but also available human resources in the organization. Its task is to determine whether technical resources match the team's capabilities and whether employees are able to transform ideas into functional systems. Technical feasibility also includes the assessment of hardware or software.
- **Economic feasibility.** Economic feasibility assessment includes an analysis of the costs and benefits that the project may bring**.**
- **Legal enforceability.** This research assesses whether any aspect of the proposed design may conflict with legal requirements**.**
- **Operational feasibility.** The assessment involves conducting an analysis to determine whether the organization's needs will be met by implementing this project. This is an important aspect focusing on the utility or functionality of the project, which should be clearly defined
- There is another aspect to the feasibility assessment:
- **Feasibility planning.** This is the last and most important stage **-** the project could fail if it is not completed within the stipulated time. When planning feasibility, the organization's task is to critically estimate how long it will take to complete the project.

Fig. 6. Main aspects of assessing the project practical feasibility [Author's]

From the point of view of the purpose of building and operating an underground gravity energy storage facility, a very important aspect is the usefulness/functionality of such a system as an element of technical feasibility. The key parameters here are electrical power and the amount of stored energy, which together determine the time of energy release by the storage facility. The complexity of the system and the simplicity of its use and maintenance are also important. A mine shaft is an element of a very complex technical system, the elements of which normally serve to achieve the basic goal of

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mineral extraction and related processes [10]. Therefore, after the end of mining, it may be necessary to preserve not only the shaft intended for gravity energy storage, but also a larger number of facilities and installations ensuring the reliable operation of the storage facility over the expected time horizon (e.g. 25 years). The need to maintain a more complex technical system may affect the available time of warehouse operation [11].

Another issue is the scalability of the technical solution understood as the possibility of enlarging (increasing the scale of operation) the system or project [12, 13]. They are not clearly defined.

4. Practical feasibility of the gravity energy storage in mine shafts

To assess the practical aspect of a gravity energy storage facility, certain functional assumptions should be made for such an energy storage facility such as energy capacity, maximum power consumed and fed back to the network. The expected life of the storage facility is at least 25 years, and the operating time with energy release is up to 4 hours (as an example of the previously described surface gravitational energy storage in Riugong). Similarly, the capacity can be assumed to be 100 MWh and the electrical power to be 25 MW. The simplest idea assumes direct use of a shaft with an existing hoist shaft and the use of a hoisting machine in the system to generate energy when lowering the load. Assuming a shaft with a permissible weight of the cage/skip, e.g. 50 Mg, a depth (actually a free path) of 750 m and a maximum travel speed (nominal) of e.g. 10 m/s, theoretically we can store in it 1MWh of energy, which, after 4 hours of operation, would enable the generation of an average power of approx. 0.278 kW. Assuming the load moves at the hoist nominal speed (excluding acceleration and braking), the energy generation time did not exceed 75 seconds with a power output of approximately 48.1 kW. Assuming the speed of movement of the weight when lowering (energy generation) at a speed of 0.1 m/s, the travel time would be 7500 s, and the generated continuous power would be approximately 0.481 kW, which is probably lower than the energy demand of the storage facility. It is worth noting that the battery energy storage, e.g. Mereus ESS - type 1, with a capacity of 1.43 MWh, weighs 28 Mg and has dimensions of 12.2x2.45x4.1 m [14]

For the same shaft (load travel distance 750 m), the necessary weight of the load was calculated, to generate energy of 25 MWh it would require using the load or loads of a total weight of approx. 1248 Mg (what in the case of steel means a volume of approx. 158-166.4 m^3). In such a variant, it would not be possible to use the shaft hoist installation (hoisting machine, tower, ropes), and in a shaft with typical diameter, e.g. 7.5 m, the total length of the steel weight would be 3.6-3,8 m, with use of the shaft full cross-section, which would exclude maintaining any necessary installations in the shaft (pipes, cables, sensors). The proposed [7] division of the load into smaller load units will require complex surface and underground installations for loading and unloading numerous loads.

In the case of the Polish hard coal mining industry, most existing shaft hoists are driven by a Koeppe Wheel, which are not optimally adapted to lowering large loads (risk of slipping of ropes on the wheel).

5. Conclusions

Despite extensive literature on energy storage in mine shafts, there is no installation of this type using an existing shaft - there are only small technology demonstrators.

Analysing the concept of gravity energy storage in mine shafts, their functionality and feasibility, the following conclusions can be drawn:

1. It is theoretically possible to use potential energy to store energy in a mine shaft, but situational feasibility is doubtful.
2. Using an existing shaft with a shaft hoist, hoisting tower, etc. for a gravity energy storage facility makes the solution not functional due to the small amount of stored energy.
3. Increasing the scale of storage in a single shaft will require very large investment costs and may appear to be technically impossible.

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4. Originators of the gravity energy storage in mine shafts often ignore the legal feasibility of such a project and the constrains resulting from the operation of shafts and shaft hoists. It does not seem possible to apply provisions less restrictive than those regarding long-term operation of shaft hoists with significant intensity.
5. Technical constrains, cost-benefit ratio in relation to high legal requirements indicate that underground gravity energy storage in a mine shaft is organizationally unfeasible.
6. The number of technical problems to be solved when creating a gravity storage facility in a mine shaft makes it impossible to plan the feasibility of such an installation, which give the same functionality as ready-made battery energy storage solutions with known operational parameters and service life, which are more attractive solution.

It should be emphasized that the use of gravity for large-scale energy storage is considered as the construction of pumped-storage power plants with reservoirs located on the surface. There is also information about the intention of commercial companies to build very large battery energy storage facilities, which indicates that gravity energy storage facilities in mine shafts are not attractive from a business perspective, which undermines their economic feasibility.

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