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## MINING EQUIPMENT DIAGNOSTICS IN A MINESHAFT DEWATERING SYSTEM – CASE STUDY

### Diagnostyka urządzeń górniczych w systemie odwodnienia szybu kopalni - studium przypadku

**Abstract:** Maintenance issues in mines are particularly important due to the type and complexity of equipment in operation or working in hostile (even extreme) conditions. In this context, the need to ensure continuous/regular maintenance of machinery, identify potential hazards and ensure operational safety seems to be a challenge. Moreover, selecting an appropriate maintenance method is crucial for a mine, both economically and in technical/organizational terms. This study aims to present the preliminary results of diagnostic tests for pumps performing operational tasks in a mine shaft dewatering system. In addition, this study focused on a detailed discussion of the basic elements of the mine shaft dewatering system and the technical objects studied. A preliminary operational test plan for the investigated pumps operating in the mine shaft dewatering system is also presented. This enabled a discussion of the results obtained from the tests of the first quarter of 2023. The tests used three basic diagnostic methods: vibration analysis, thermal imaging and acoustic testing. Potential directions for further research in the analyzed area were also indicated.

**Keywords:** maintenance, mining industry, pump maintenance, diagnostics, mine shaft dewatering system

**Streszczenie:** Problematyka utrzymania ruchu w kopalniach jest szczególnie istotna ze względu na typ i złożoność eksploatowanych urządzeń czy pracę w nieprzyjaznych (wręcz ekstremalnych) warunkach operacyjnych. Wyzwaniem w tym kontekście jest konieczność zapewnienia ciągłych/regularnych napraw maszyn, identyfikacji potencjalnych zagrożeń oraz zapewnienia bezpieczeństwa pracy. W tym kontekście, dobór odpowiedniej metody utrzymania ruchu ma kluczowe znaczenie dla kopalni, zarówno w kontekście ekonomicznym



*jak i techniczno-organizacyjnym. Celem pracy jest więc przedstawienie wstępnych wyników badań diagnostycznych przeprowadzonych dla pomp realizujących zadania operacyjne w systemie odwodnienia szybu kopalni. W ramach realizacji celu pracy skupiono się na szczegółowym omówieniu podstawowych elementów systemu odwodnienia szybu kopalni oraz badanych obiektów technicznych. Przedstawiono również wstępny plan badań eksploatacyjnych dla badanych pomp, funkcjonujących w systemie odwodnienia szybu kopalni. Pozwoliło to na omówienie uzyskanych wyników badań, przeprowadzonych w pierwszym kwartale 2023 roku. Badania zostały opracowane z wykorzystaniem trzech podstawowych metod diagnostycznych: analizy drgań, termowizji oraz badań akustycznych. Wskazano również potencjalne kierunki dalszych prac badawczych w analizowanym obszarze.*

**Słowa kluczowe:** utrzymanie ruchu, przemysł górniczy, utrzymanie pomp, diagnostyka, system odwodnienia szybu kopalni

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## 1. Introduction

A significant problem in the context of the safe and efficient operation of mines is the selection of an appropriate maintenance method for machinery and equipment operating in hostile conditions. This problem is highlighted in the context of ensuring occupational safety (e.g. [1]) or the economic efficiency of the mining process (e.g. [2]). A literature review in field of applicable mining Acts, regulations and standards is presented in [3].

Due to the presence of many maintenance strategies - from a reactive approach to a predictive maintenance strategy, one of the basic decision-making dilemmas in this area is the appropriate selection of a maintenance approach tailored to the needs and capabilities of mining companies [2, 4]. This problem was investigated, e.g. in works [5–7], where preventive maintenance and inspection policies were analyzed. Implementation possibilities of condition-based maintenance approach in mining companies were discussed in [8–11]. Implementation possibilities of predictive maintenance were reviewed, e.g. in [12–14]. In addition, many works focus on predictive maintenance implementation and diagnostic/early warning methods in application areas, such as fan failure prediction (e.g. [15]), gearbox maintenance (e.g. [9]), bearings diagnostics (e.g. [16]), or mobile mining equipment maintenance (e.g. [17–19]). In addition, works focusing on Industry 4.0 technologies and the use of artificial intelligence in the maintenance of mining equipment can also be identified (see e.g. [20–22]).

At the same time, in both scientific and application aspects, one of the main problems in ensuring continuous operation in mining companies is the technical maintenance of

pumps in mine shaft dewatering systems. The problems of pump reliability and diagnostics are broadly discussed with selected examples in [23]. The author focused on presenting several case studies for centrifugal pumps and reciprocating pumps. A literature review of predictive maintenance of pump systems was also illustrated, e.g., in [24, 25]. However, the authors focused on analyzing heat pumps operating in combined heat and power plants. The maintenance problem of large-scale heat pumps is summarized in a review article [26]. Currently, there are no works on the maintenance problem of pumps operating in mine shaft dewatering systems in a broader context. Examples of mine-specific solutions worldwide can be found, for example, in [27], where the authors compared basic dewatering systems for coal mines operating in India. The paper focuses on the efficiency of the studied solutions.

In this context, the paper deals with the problem of dewatering pump maintenance. The paper aims to present preliminary results from the diagnostic tests carried out for pumps performing operational tasks in a deep mine shaft dewatering system and equipment for the onward transfer of pumped water.

In the next literature section, a review of mining pump maintenance is presented. Later, the mine shaft dewatering system is discussed with a detailed presentation of the technical objects for diagnostic evaluation. Next, the problem of implementing diagnostic tests of the technical objects under analysis is discussed. A predetermined diagnostic test plan was presented, and test results were discussed. The chapter concludes with a summary and potential directions for further research in the analyzed area.

## **2. Dynamic pump maintenance – literature review**

In mining, mineral sludge, wastewater, kaolin slurries, or compacted sludge must be dealt with by suitable pumping systems and equipment. Therefore, many types of pumps in the mining industry are designed for pumping clean and contaminated water as well as sludge with various muds. These pumps have to meet the requirements of each substance, and the safety of workers and the efficiency of their work depends on the quality of the applied pump and the correctness of the conducted maintenance processes [28, 29]. Not to mention that machinery and equipment operating in the mining industry are also exposed to many detrimental factors, e.g. salts, dust, humidity, and high temperatures. To meet these requirements, these systems are designed so that their sensitivity to these factors is as low as possible. Therefore, due to the difficult operating conditions, maintenance issues become particularly important in the case of such systems [27].

In addition, pumps can be classified into two main groups: dynamic (non-positive displacement) pumps and positive displacement pumps [30]. The first group of pumps use the fluid velocity and the resulting momentum to generate the pumping power and move

the fluid through the system. The second type of pump can operate by forcing a fixed fluid volume from the pump's inlet pressure section into the pump's discharge zone [30, 31]. In another work [32], the authors provide a more detailed classification of pumps based on three group definitions: rotodynamic pump, positive displacement pump, and other pumps (impulse pump, gravity pump, steam pump, and valveless pump). In the analyzed case, the dynamic pump maintenance case is investigated.

In the context of dynamic pump maintenance, two basic maintenance approaches are currently used in the mining industry: the so-called 'run to failure' or Corrective Maintenance (CM) strategy and the Preventive Maintenance (PM) strategy [33]. When the first approach is used, it is associated with a pump failure, including financial, time-related, and human safety implications. In the case of a preventive maintenance strategy, especially when implementing a time-based PM approach, a situation may arise where pump parts are replaced not because they are about to fail but because their planned service life has expired, which may be a suboptimal maintenance method due to the cost of parts, labour and time investment. In addition, due to unforeseen circumstances, pump parts may fail between overhauls, resulting in catastrophic events [33].

Another approach widely used in mining pump maintenance is Condition-based Maintenance (CBM), which is based on monitoring the parameters that define the technical condition of a system or its components using diagnostic methods/measures [34, 35]. For selected cases, the CBM strategy even offers the possibility of implementing maintenance activities before the system/its components fail. In contrast to corrective maintenance strategies CM or preventive maintenance PM, CBM focuses on fault detection and component diagnosis, monitoring the degradation process and predicting potential failures. These issues are addressed in the works [36–38].

Another approach is based on a predictive/predictive maintenance (PdM) strategy [39, 40]. Its main task is monitoring the system's operating conditions to detect any signs of wear and predict faults or failures in the degrading system [23]. The latest diagnostic methods allow the condition of the machines to be monitored continuously which makes it possible to predict pump failures in advance [41]. Continuous monitoring of operating parameters allows corrective action to be taken, e.g. change of settings or lubrication. The most commonly used diagnostic tests are thermal, vibration and acoustic measurements [42]. The issue of predictive maintenance of pumps has been analyzed, among others, in works [12, 43]. A comprehensive review of fault diagnosis in the pumping systems is given, e.g., in [32, 44]. However, not much work is dedicated to the problems of mining pump maintenance [45].

### 3. Maintenance tests of mine shaft dewatering system – case study for pump diagnosis

#### 3.1. Mine shaft dewatering system

In the context of the research work, the authors focus on the mine dewatering pumping station system, a general diagram of which is shown in Figure 1.

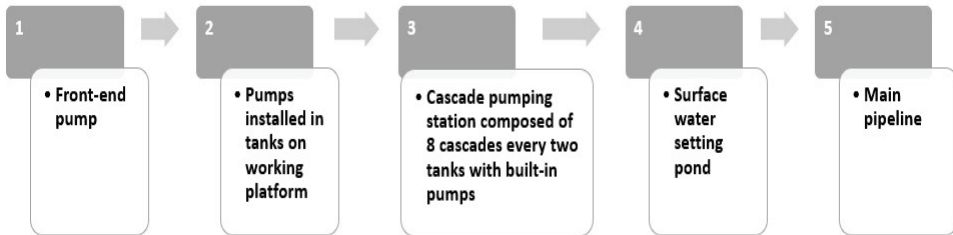


Fig. 1. Scheme of the shaft dewatering system

Within the conducted diagnostic tests, the authors focused on two areas of the shaft dewatering system: the pumping installation built in the settling pond for Surface water (element 4, Fig. 1) and the cascade pumping station (element 3, Fig. 1).

The subject of vibration diagnostic testing is the NB-45 pump (item 4, Fig. 1), designed to operate in the pumping system for liquid collected from the shaft yard and water from the dewatering process. More information can be found in [45].

The surface water pumping station is located next to the surface water settling pond. It has three pumps connected in parallel to a pipeline that connects to the primary transmission mainline. A schematic of the construction of the pumping station, including the settling pond, is shown in Figure 2.

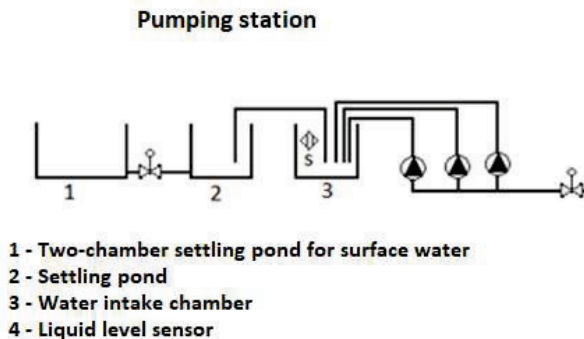


Fig. 2. Layout of the pumping station

At the same time, acoustic tests were carried out in the shaft pipe where the cascade pumping station is built (element 3, Fig. 1).

A cascade pumping station is a system responsible for removing excess water from a deep shaft. It is currently built with 8 levels (target) on which two BS - 2400 pumps are being built in 1.5 m<sup>3</sup> tanks. This system was expanded as the shaft continued to be deepened. The cascades are installed every 150 m as determined by the technical parameters of the installed pumps.

### **3.2. Maintenance tests for pump operating in mine shaft dewatering system**

The diagnostic tests focused on three test methods:

- vibration diagnostics,
- thermal analysis,
- acoustic testing.

The tests were planned and conducted based on the main standards, i.e.:

- ISO 9614-2:1996 Acoustics - Determination of Sound Power Levels of Noise Sources Using Sound Intensity - Part 2: Measurement by Scanning [46],
- ISO 4412/1 Hydraulic fluid power - Test code for determination of airborne noise levels. Part 1: Pumps [47],
- ISO 10816-1:1995 Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts — Part 1: General guidelines [48],
- ISO 20816-1:2016 Mechanical vibration — Measurement and evaluation of machine vibration — Part 1: General guidelines [49].

A detailed description of the diagnostic test plan is presented in [45]. In the next Section, there are presented preliminary results of the performed vibration and acoustic tests.

### **3.3. Obtained results for pump maintenance tests**

The first step focused on vibration test performance. The tests on the real objects started on 12.02.2023. The first carried-out test was to check the initial assumptions set out at the planning stage of the tests and to make any corrections. Data collection during the analysis period took place weekly, depending on the possibilities and the work currently being carried out in the pumping system. The equipment subjected to analysis was in various operational conditions. The core of the investigation is the identification of critical points for a group of analyzed objects. Their different condition makes it possible to analyze differences from a broader perspective and draw conclusions from the events. The measurements were carried out on individual pumps.

The first diagnostic step that can be carried out without measuring instruments is to check the capacity, pressure and flow that each pump generates and compare them. Observation of these parameters is straightforward as they are controlled by sensors in the pipeline. These data are shown in Table 1.

Analyzing the results shown in Table 1, it can be seen that pump No. 1 is the pump with the lower flow capacity, and its condition in relation to the other pumps differs significantly. On 11.03, it can be seen that there was a jump in the capacity of each pump due to the cleaning of the suction baskets in the intake chamber from which the pumps draw water. A measurement taken on 19.03 on pump No. 3 shows a sudden performance increase caused by replacing the pump and motor. The reason for the replacement was the appearance of a leak on the pump body.

**Table 1**

**Initial results of pumping water flow observed during the diagnostic tests**

Date	Water flow [m <sup>3</sup> /h]		
	Pump no. 1	Pump no. 2	Pump no. 3
12.02.2023	32.8	42.5	40.0
19.02.2023	32.6	41.5	38.5
27.02.2023	32.8	43.8	39.3
06.03.2023	31.8	41.2	38.2
11.03.2023	32.6	42.3	42.3
19.03.2023	32.3	41.5	46.6

Another parameter analyzed was the pressure measured on the individual pumps. This measurement is averaged because the values were not stable. The obtained results are shown in Table 2.

**Table 2**

**Initial results of pumps' pressure observed during the diagnostic tests**

Date	Pressure [hPa]		
	Pump no. 1	Pump no. 2	Pump no. 3
12.02.2023	10 000	12 000	11 500
19.02.2023	10 500	12 000	11 500
27.02.2023	10 000	11 800	12 000
06.03.2023	10 300	12 400	11 800
11.03.2023	10 500	12 000	12 300
19.03.2023	10 400	12 500	12 900

The results indicate that the technical condition of pump No. 1 differs significantly from the others. This state is likely to be caused by wear on the pump rotor and leaks on the pump itself. This fact can only be determined after disassembly and corrective action performance.

The next diagnostic test measured the vibrations of the electric motor that drives the pump. Measurements were taken at the points closest to the bearing positions of the motor shaft. Points 1 and 4 are located at bearing no. 1, and points 2 and 3 at bearing no. 2. Additional measurements are taken in the x, y, and z axes at bearing no. 1, which are located on the mounting collar (Figure 3). Exemplary results are given in Figures 4-5.

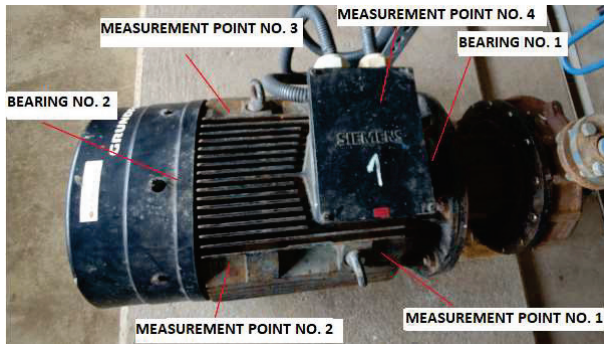


Fig. 3. Identification of the measuring points

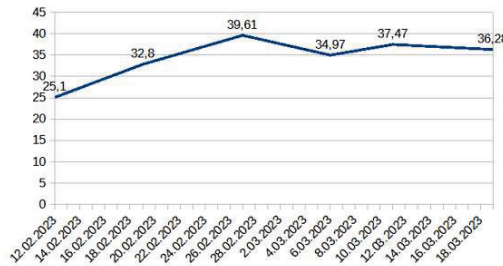


Fig. 4. The curve of accelerations observed at measuring point no. 1

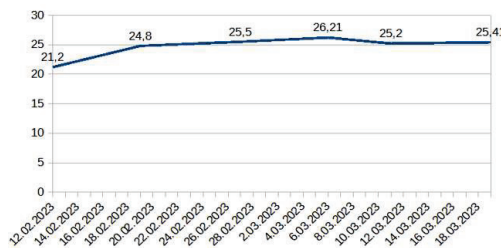


Fig. 5. The curve of accelerations observed at measuring point no.

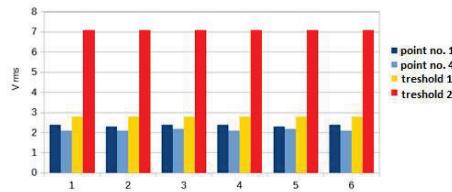


The most important parameter in vibration diagnosis is the effective vibration velocity  $V_{rms}$ . The ISO 10816-1 standard defines vibration ranges for individual machine categories. The analyzed machine falls into equipment class II, for which the vibration values are respectively:

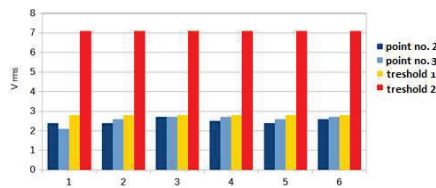
- up to 1.12 - good condition
- 1.12 to 2.80 satisfactory condition
- 2.80 to 7.10 unsatisfactory condition
- from 7.1 unacceptable condition.

The vibration velocities for the individual points of the respective bearing node are shown in Figures 6-8. On the graph, these were defined as:

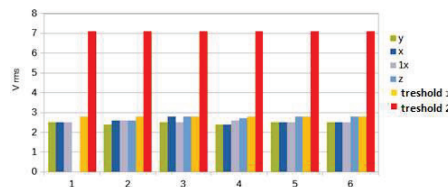
- threshold 1 - corresponds to a limit value of 2.8m/s. This is the value between satisfactory and unsatisfactory condition.
- threshold 2 - corresponds to a limit value of 7.1 m/s. This is the value after which the unit must be taken out of service.



**Fig. 6.** Vibration speed for bearing no. 1, measurement points no. 1 and 4



**Fig. 7.** Vibration speed for bearing no. 2, measurement points no. 2 and 3

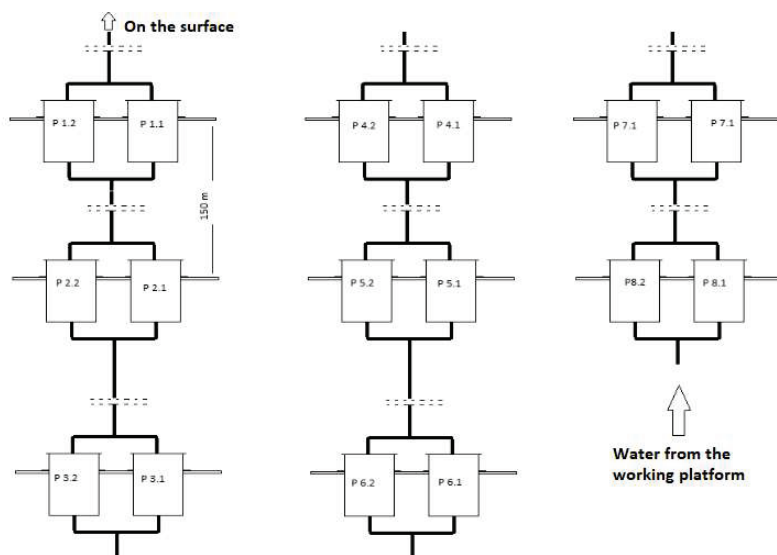


**Fig. 8.** Vibration speed for bearing no. 1, measurement points in the x, y, z axes

After analyzing the individual plots, it can be seen that some velocities approach but do not exceed 2.8 mm/s at several points. According to the standard, the machine falls into condition class B.

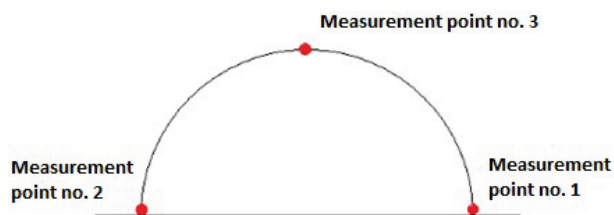
The second step focused on carrying out a preliminary acoustic test. The measurement work, which consisted of diagnosing the pumps operating in the cascade shaft dewatering system, started on 12.02 and was repeated at interval of about a week, depending on the possibilities and the ongoing work in the shaft. Carrying out the tests meant no other people could work at the bottom of the shaft since it posed a danger to those working below.

For the diagnosis of the pumps of the cascade dewatering system, 6 units installed on 3 different cascades were selected. The first cascade is located at a depth of 150 from the shaft level and each subsequent cascade is also the same distance away from the others. In total, there are eight such cascades in the shaft. Two BS-2400 pumps in 1.5 m<sup>3</sup> tanks are installed on each platform. They are supplied with 1000 V. All pumps are connected to a common DN150 pipeline running the full depth of the shaft. The system works by pumping water from the lower levels upwards until the water reaches the surface. During this process, only one pump can operate per cascade (Figure 9).

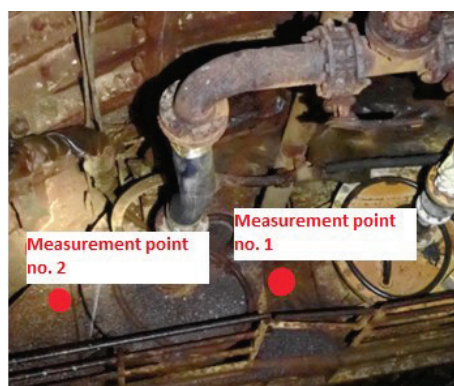


**Fig. 9.** Scheme of the shaft dewatering system - cascade system of pumps

Measurements were taken using a TROTEC SL400 acoustic microphone with dedicated software. The first measurements were implemented to make necessary adjustments to the defined test plan (see [45]). The location of the measurement points is shown in Figures 10-12.



**Fig. 10.** Location of measuring points above the pump under test



**Fig. 11.** Location of measurement points no. 1 and 2



**Fig. 12.** Location of measurement point no. 3

The biggest difficulty in taking measurements was the overwhelming humidity and water, which caused damage to the PC in the first phase. Further testing required appropriate precautions to protect the measuring equipment. As far as possible, intake ventilation was used, because with this method of ventilating the shaft, the humidity level was considerably reduced, and measurement work was facilitated. Performing tests in this type of environment is an activity that requires a great deal of attention on the part of the tester, as the equipment can be quickly damaged.

Measurements on each pump were taken at three points at a distance of 200 mm from the pump. In addition, the pump's electric current and pressure were taken into account for the analysis. The pressure measured on a given pump is the value with which the preceding pump delivers water to the tank. The lower the pressure, the faster the pump picks up the delivered water. Seven measurements were taken at different intervals for pumps no. 1.1, 1.2, 2.1, 2.2, 3.1, 3.2 during the analysis period. In Tables 3-4, results for pumps 1.1 and 1.2 were presented.

**Table 3**

**Initial results of obtained diagnostic tests for pump no. 1.1.**

Date	Background acoustic power	Point no. 1	Point no. 2	Point no. 3	Electric current	Pressure
	dB	dB	dB	dB	A	kPa
12.02.2023	68	80	81	80	52	5
19.02.2023	66	80	80.5	81	52	3.75
27.02.2023	64	81	77.94	78.21	56.7	4.45
06.03.2023	63	76.1	-	-	58	62
11.03.2023	65	80.3	79.01	-	54	5
22.03.2023	67	81.12	81.89	77.58	53	58
02.04.2023	66	79.4	77.5	-	58	28

Analyzing the obtained results (Table 3), it can be seen that the noise level remains constant at around 80 dB. The background acoustic level was measured before pump operation and oscillated around 65 dB. The background acoustic level consists of all the sounds prevailing in the shaft, i.e. the air flow in the brazing pipeline supplying air to the face of the shaft, as well as numerous other sounds.

**Table 4**

**Initial results of obtained diagnostic tests for pump no. 1.2.**

Date	Background acoustic power	Point no. 1	Point no. 2	Point no. 3	Electric current	Pressure
	dB	dB	dB	dB	A	kPa
12.02.2023	68	78	77	79	53	120
19.02.2023	65	81.8	80.5	81.4	55.3	110.6
27.02.2023	65	79.55	79.65	78.54	57.1	158
06.03.2023	62	81.05	-	-	53	130
11.03.2023	64	76.92	76.73	-	54	140
22.03.2023	65	81.45	83.29	78.13	54.5	140
02.04.2023	67	79.4	79.2	-	59	26

Pumps 1.1 and 1.2 operate at the same depth level, but despite similar operating conditions, a difference can be seen in the pressures experienced by the two pumps. Such high pressures are an alarming symptom for the operator, who should take corrective action. At the time of the measurements, there was not such a significant increase in pressure that would cause the excess water to overflow the drain, but such situations did occur. Missed measurements at points 2 or 3 were due to high pressure, which could cause water to overflow, or high humidity levels in the shaft. Measurements were interrupted out of concern for the measuring equipment or in a rush. On 22.03, maintenance work was undertaken on pump 1.2 to check the condition of the equipment, i.e., the compensator and the return flap. Frequent causes of rising pressures at the pump are damaged or blocked check valves or compensators that, due to material defects, restrict the flow to such an extent that it blocks it completely. When these measurements were taken and found to be working properly, it was decided to replace the pump. This fact can be seen in the measurement on 2.04, where the recorded pressure on the tank was 26 kPa. No amount of sludge that could block the flow was observed on the disassembled pump. The likely cause of the low pump performance could be a worn-out rotor.

At the same time, it should be noted that the pressure measurement at the pump is not the actual pressure the pump generates but only the difference between the water supplied from the cascade below and the the pump's capacity that receives this water. Therefore, in the diagnostic process, a pressure gauge is fitted to the pump's discharge port to check the actual pressure the pump generates. However, this measurement, is not entirely reliable as, over time, the operating device will reach the desired value.

The testing procedure in the investigated mine shaft dewatering system is also worth mentioning. During the diagnostic phase, the dewatering system operated differently from the real-life conditions. The present process involves collecting water in the shaft and pumping it out once a day. It meets the same operating conditions for the entire system over a long period. However, such a state of affairs does not occur in a normal process cycle, and the system can't operate long without short breaks to refill the tanks. Improper switching of pumps in the running system results in increased pressure in various parts of the system, with the risk of unexpected water overflow. Such an incident occurred on 6.03, where an operator switching pumps unbalanced the entire system, causing system instability and overflow.

## **4. Conclusions**

The paper focuses on the discussion of maintenance issues of pumps used in the mine shaft dewatering system. First, the selected cascade mine shaft dewatering system is characterized, and the results of diagnostic tests for pumps operating in the analyzed system

are presented. The tests were based on two diagnostic methods: vibration diagnostics and acoustics. In the first step, the obtained results allowed for preliminary verification of the assumptions of the developed research plan presented in the paper [45].

According to the obtained results, it can be stated that the diagnosed pumps are in different technical conditions and with different periods of operation, which can clearly be observed from the noises emitted by these pumps or the pressure levels raised. A likely cause of the high pressures may be the current dewatering method. The removal of water once a day forces the system to stand still for the rest of the day, which means there is a possibility of solids settling on the pumps or other equipment and subsequently blocking the water flow. Systematic water movement, however, eliminates such phenomena or reduces their occurrence to a minimum.

At the same time, the problems identified during the tests and the conclusions obtained will be used to determine critical symptom values for the pumps in operation. The identification of these conditions will allow maintenance services to react appropriately and start corrective actions to restore the process operation. Carrying out diagnostics of the cascade system without installing additional equipment or conducting tests directly on the pump with the help of equipment is important in the operation of the entire technological process. The elaboration of the obtained test results will help improve the operation of the maintenance services and may be a reason to change the overall operation of the maintenance department.

In the next steps, the authors will focus on developing guidelines for a proactive maintenance method for mine pumps operating in a mine shaft dewatering system based on a condition-based maintenance approach and fault prognosis possibilities.

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