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EVALUATION OF THE EFFICIENCY OF IMPACT MECHANISMS ON THE EXAMPLE OF HYDRAULIC DRILLS AND HYDRAULIC HAMMERS

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Abstract:
The efficiency of energy transfer in impact mechanisms, often referred to as impact engines, is of key importance to users of these devices, including hydraulic impact hammers. The selection of a method that enables accurate and repeatable determination of the impact energy and impact frequency as functions of supply parameters (supply pressure and supply flow rate) is a critical issue, ultimately allowing for the assessment of the efficiency of these devices. To address this, an analysis was carried out of the available analytical, analytical-empirical, and empirical methods, along with their associated measurement systems. Based on this analysis, the authors proposed an original method, based on the empirical determination of impact energy and impact frequency as functions of supply pressure and flow rate. For the purposes of this method, a concept, design, and documentation of a mobile measuring station were developed, enabling onsite testing of hammers at their place of operation. Subsequently, appropriate tests were carried out using this station. Based on the measurement results, the mechanical, hydraulic, and overall efficiencies of the tested hammers were determined. This approach allows performance assessment of the tested hammers and supports decisions regarding their continued use or the need for overhaul.

Keywords: *hydraulic rotary-percussive drills, hydraulic impact hammers, determination of impact energy, force sensor*

1. INTRODUCTION

Impact mechanisms, often referred to as impact engines and exemplified by impact

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hammers, are used to generate and transmit impact energy of a specified magnitude and frequency. The reciprocating motion of the piston, also referred to as the striker, is driven by compressed air or by a stream of hydraulic fluid. The collision of the striker with the tool results in the transfer of impact energy, which is utilized for the fragmentation of artificial or natural materials (material disintegration). In such cases, the device is referred to as a pneumatically or hydraulically driven impact hammer (Bęben, 1992; Szykowny, 2006; Sokolski, 2013).

Users are primarily interested in functional parameters, namely the impact energy Eu and impact frequency fu, as well as supply parameters, including supply pressure pzu and flow rate qzu of the medium (compressed air or hydraulic oil).

The aforementioned parameters should be specified by the manufacturer together with the method of their determination. This particularly applies to the determination of impact energy, as this parameter can be determined analytically, empirically, or analytical-empirically (Rammer, 1997).

The determination of impact energy is the most controversial, as it can be determined by various methods, but the results are not comparable. Hence, it is necessary to apply a consistent method for different impact engines so that impact energy measurement results can be compared. This applies to new equipment at the time of purchase as well as during subsequent operation. Furthermore, the assessment of a hammer's technical condition during operation – particularly in determining whether it should continue to be used or be refurbished (or replaced) – requires the determination of its actual operating parameters, i.e., the measured impact energy Eum and impact frequency fum as a function of its supply parameters: pressure pzm and flow rate qzm. This is possible by utilizing dedicated stationary or mobile test benches (Korzeń et al, 1984).

2. METHODS FOR DETERMINING IMPACT ENERGY AND IMPACT FREQUENCY

In Poland and the European Union, there is no requirement to apply a single standardized method for determining impact energy. This obligation rests solely with manufacturers, who determine this parameter in various ways and report it in their commercial documentation.

The least accurate results for impact energy are obtained from analytical models, where it is determined as the product of the ram mass and its velocity. This is a theoretical value at the ram–tool interface, often overestimated, as it includes the maximum ram velocity in the calculations instead of the velocity at the moment of impact. Furthermore, the calculations omit the dissipation of impact energy upon striking the tool's rear end and the influence of losses associated with the propagation of the stress wave (longitudinal stress wave) in the bit or rod (Bęben, 1992; Szykowny, 2006; Sokolski, 2013).

A commonly used approach involves measurements with strain gauges mounted on the rod, bit, or an intermediate element. Strain gauge measurements, when properly applied and calibrated, allow for obtaining accurate and repeatable results. However, the measurement location and calibration method influence the results obtained. In practice, the measurement system using strain gauges is prone to rapid damage or failure. Manufacturers using this method typically do not disclose detailed measurement procedures, making it impossible to achieve repeatability for comparing results. Methods using strain gauge measurements can be found in Polish Patent No. 146814 "Device for measuring the impact energy of hydraulic hammers" from 1984 and in the EPTA-05/2009 procedure developed by the European Power Tool Association for electro-pneumatic hammers (Krauze et al, 1996, 1997a, 1997b, 1999, 2001).

An interesting indirect measurement procedure is the method used by the CIMA CIMA (Construction Industry Manufacturers Association), which is applicable in the USA. This method is based on measuring the stress wave generated by the ram's impact on the bit. As it propagates along the tool, the stress wave is measured by a system of strain gauges mounted to the bit. The CIMA organization specifies that the determination of impact energy involves measuring the stress wave generated in the bit after the ram's impacts, as a representation of the energy transmitted through the bit. This method has been applied to measure the impact energy of hydraulic hammers. Based on their research, CIMA has demonstrated significant discrepancies between values provided by manufacturers and measured values. The differences reaching up to 49% (Krauze et al, 1996, 1997a, 1997b, 1999, 2001).

The application of this method, despite being recognized by leading manufacturers of hydraulic hammers, allows only for the direct measurement of energy and indirect measurement of impact frequency. It should also be noted that each measurement requires the application of strain gauges, which is a significant practical limitation. The application of strain gauges must be performed precisely, and the entire system comprising the hammer, bit, and strain gauge sensor must undergo a calibration process. A second disadvantage of the above method, observed in practice by the authors, is the low durability of the applied strain gauges, which are rapidly damaged due to overloads during the energy transfer from the ram to the bit (elastic impact).

• The aforementioned limitations of this method and other methods (Rammer, 1997; Korzeń et al, 1984) motivated the development of a solution enabling accurate, reliable, and lowcost measurement of the impact energy and frequency of impact hammers. Hence, in response to the needs of KGHM Polska Miedź, O/ZG Rudna, a stationary diagnostic stand for hydraulic impact hammers was developed in the 1990s. This stand allowed, in addition to measuring impact energy and frequency as a function of supply parameters, for the identification worn kinematic pairs requiring replacement (Krauze et al, 1996, 1997a, 1997b). The problem with this stand was the necessity of transporting the hammer for testing, even if it was not yet malfunctioning, and then returning it to its place of use. This resulted in the user, not the supplier or manufacturer, bearing the costs of servicing and repair of the hammer. Therefore, based on the experience gained during research conducted on the stationary diagnostic stand, efforts were undertaken to develop a mobile stand for measuring impact energy and frequency as a function of supply parameters was undertaken.

3. ASSESSMENT OF THE TECHNICAL EFFICIENCY OF IMPACT ENGINES

As mentioned earlier, a user intending to employ impact hammers must establish their requirements regarding the relevant technical parameters of these devices. They can then evaluate, based on energy efficiency, which device best meets these requirements. Subsequently, when operating these devices (hammers and drills), the user should have the capability to assess their level of wear.

It is assumed that the total (energy) efficiency η_{co} of an impact engine is expressed by the general relationship (Szykowny, 2006):

$$\eta_c = \eta_h \cdot \eta_m \tag{1}$$

where:

η_h – efficiency of the internal hydraulic system of the hammer (hydraulic efficiency)

η_m – efficiency of the ram-tool-rock system (mechanical efficiency)

$$\eta_h = \frac{E_u \cdot f_u}{p_{zm} \cdot q_{zm}} \tag{2}$$

where:

E_u – impact energy [J],

f_u – impact frequency [Hz],

p_{zm} – fluid pressure at supply [MPa],

q_{zm} – fluid flow rate at supply [dm^3/min]

In the case of bench tests, the hydraulic efficiency η_h is of interest and is expressed by the relationship:

$$\eta_h = k_p \cdot k_\Theta \tag{3}$$

where:

k_p – proportionality coefficient of the impact energy and the power supply pressure [kJ/MPa]

k_Θ – proportionality coefficient of the frequency and the flow rate of the fluid at the supply [1/dm^3]

then:

$$E_u \approx k_p \cdot p_{zm} \tag{4}$$

$$f_u = k_\Theta \cdot q_{zm} \tag{5}$$

Determining the aforementioned efficiencies of the impact mechanisms allows for the assessment of their operational efficiency, both during the selection of these devices and during operation. In the proposed procedure for testing the efficiency of hammers, the primary focus is placed on determining the impact energy, anticipating the potential use of the previously applied testing method, measurement system, and measurement procedure in mobile test rigs for hydraulic hammers (Łuczko et al, 2003; Siwulski et al, 2022; Franca, 2011; Xi et al, 2022; Zhang et al, 2019; Karpov et al, 2021; Oparin et al, 2017).

3.1 IMPACT ENERGY MEASUREMENT OF HYDRAULIC IMPACT MOTORS (IMPACT HAMMERS, IMPACT DRILLS AND ROTARY IMPACT DRILLS)

An indirect method was chosen for measuring the impact energy of hammers and drills, based on measuring the strain using a strain gauge transducer placed beneath the bit or rod of the tested device. The application of a separate strain gauge transducer eliminates the previously mentioned limitations and drawbacks of earlier solutions.

This transducer consists of two parts (Fig. 1). The first element, in the shape of a stepped shaft 1 with attached strain gauges, constitutes a traditional transducer for measuring strain (forces) caused by external loads. The second element, placed on the measuring shaft 1, has the shape of a cylinder 2, inside which an elastic element 3 is located. From the top, the cylinder 2 is closed by a cover 4, on which the bit of the impact hammer rests. The shape of the transducer and the number of its elements are dictated by the value and duration of the measured strains, as well as by reliability and durability requirements.

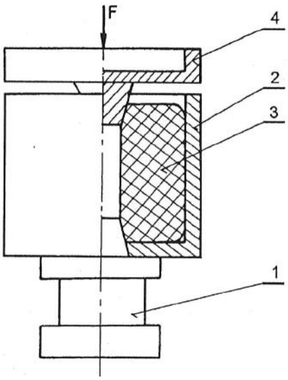

Fig. 1. Construction diagram of the energy (force) sensor

For calibrating the transducer, the principle of equivalence between kinetic energy (measured) and potential energy (calibrating) is employed. Calibration is performed on a test stand whose construction allows for the free dropping of a calibration mass m_w from a specified height onto a strain gauge transducer of mass m_c.

The energy transferred to the transducer causes a stress wave σ_{cw}, which is measured by a system of strain gauges. The correlation between the reference energy E_w and the measured energy E_m as well as between the corresponding reference and measured stresses, can be written as (for flat contact surfaces):

$$E_m = E_w \left(\frac{P_m}{P_w}\right)^2 \tag{6}$$

where:

P_m - measured force [N],

P_w - calibration force [N].

From relations (6), it follows that for a single calibration energy E_w (h_w = const.), the value of strain or force signals must be accurately determined (using the least-squares method) in order to subsequently determine analytically the value of the measured energy, when the waveform of P_m from the conducted measurements is known.

During hammer testing, the impact energy of the hammer (ram, m_b) is transmitted to the sensor via an adapter (tool/indenter) or, in the case of drilling machines, through the drill rod. The introduction of an additional adapter mass m_g necessitates its consideration in the calibration coefficients, as the actual energy transferred to the transducer through the adapter or drill rod is determined by the theory of impact:

$$E_g = \frac{4 \cdot m_g \cdot m_w}{(m_g + m_w)^2} \cdot E_w \tag{7}$$

When determining the hammer energy, it is also necessary to consider that the force transducer is subjected to forces originating from the hammer mass and any applied preload. The magnitude of the stresses induced by these forces (P_n) corresponds to an equivalent energy. Therefore, the measured hammer impact energy (E_m) must be reduced by this equivalent energy component.

$$E'_m = E_m - E_n \tag{8}$$

The final relationship for determining the impact energy has the form (Krauze et al, 1999):

$$E'_m = \frac{4 \cdot m_g \cdot {m_w}^2}{m_b \cdot (m_g + m_w)^2 \cdot {A_w}^2} \cdot \left({A_m}^2 - {A_n}^2\right) \cdot E_w \tag{9}$$

where:

A_w, A_m, A_n - the signal values [mV] corresponding to the forces P_w, P_m, P_n,

These dependencies enable the use of a single transducer calibration, performed in energy units, in instances where the calibration parameters deviate from the parameters of the hammer under test. These discrepancies can be accounted for by applying appropriate conversion factors.

3.2. MOBILE MEASURING STATION FOR HYDRAULIC IMPACT HAMMERS

Hydraulic impact hammers, in contrast to rotary-percussive drills, are exclusively designed for the disintegration of irregularly shaped natural or artificial materials. Consequently, they are regarded as impact motors that generate impact energy at a specified frequency. Their masses vary, depending on the required impact energy output. These hammers are most frequently installed on stationary or mobile booms. The previously described procedure for conducting measurements and evaluating the technical condition of the impact motor, specifically by determining its efficiency in this case, was also applied here. Such a test rig was developed at AGH, commissioned by KGHM Polska Miedź S.A., O/ZG Rudna, complete with a dedicated experimental methodology, including the measurement of impact energy and frequency, supply pressure and flow rate, and the necessary equipment (a mobile measurement station).

The mobile test rig for hammer testing, incorporating a suitable measurement system, enables testing to be performed at the hammers' operational site. The boom supporting the hammer functions as a lifting element (Fig. 2).

As previously mentioned, the objective of these investigations is the nonintrusive determination of the functional parameters of hydraulic impact hammers through measurement. Consequently, the mobile test rig has been equipped with a measurement and recording system for the acquisition of impact energy and frequency, pressure on the supply and return lines, and flow rate on the supply and return lines.

The waveforms of the measured quantities are acquired and recorded using an appropriate measurement system. In contrast, the impact energy, to ensure accuracy and repeatability, is determined indirectly, through the measurement of stresses in a force transducer induced by the collision of the ram with the adapter.

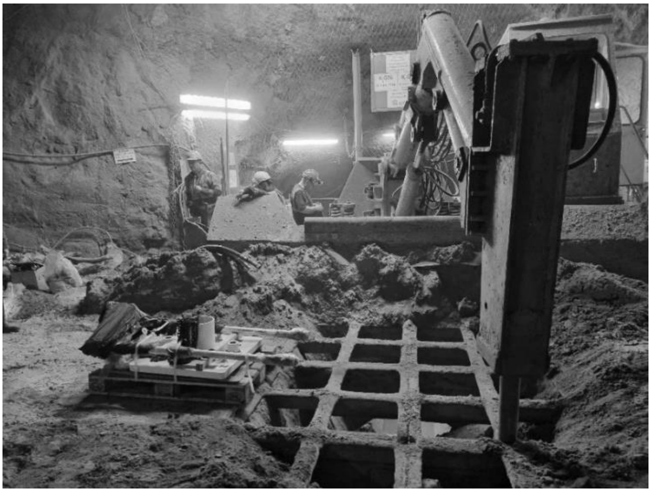

Fig. 2. The unloading point of mined material, popularly called the grate, O/ZG Rudna

The measurement station comprises two main subsystems. The first component is the mobile force sensor MPS/E1, together with a calibration system and supporting structure (Fig. 3a). A force transducer incorporating an elastomer insert is centrally mounted on a fixed base (supporting structure) equipped with sockets and a stabilizing plate (Fig. 3b). Furthermore, a guide assembly with a reference mass is attached to the plate during the calibration procedure.

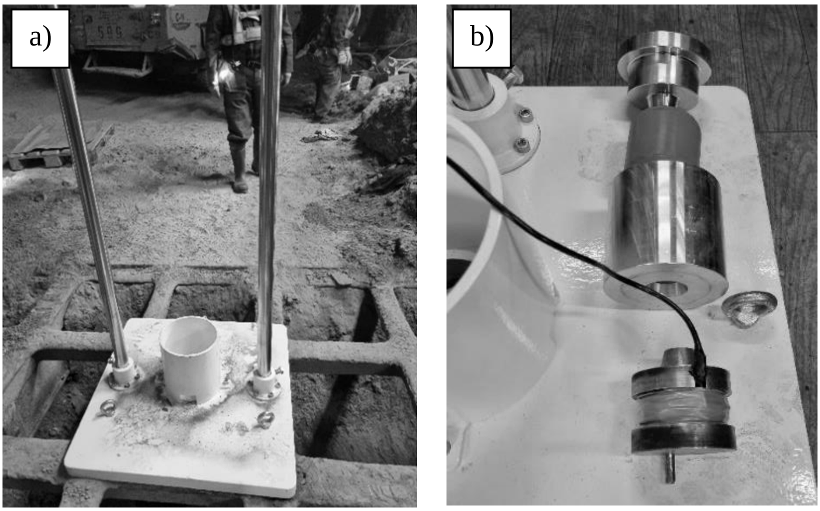

Fig. 3. Assembly: a. supporting structure (base) positioned on a grating,
b. force sensor equipped with an elastomer insert.

The second component of the station is a measurement system comprising a measurement data logger (KOM-22 UDM), a temperature sensor (APT-28/GB.PD/L=70/G1/2), pressure transducers on the supply (PC-28/PD/0-25M/0-10/G1/2) and return (PC-28/PD/0-1M/0-10/G1/2) lines, and flow rate transducers on the supply (Hoffer, HO1x1-4-60-C-1M-NPT-IND-CE) and return (Hoffer, HO1x1-4-60-C-1M-NPT-IND-CE) lines, which are mounted on the hydraulic lines (Figs. 4, 5). Signals from these transducers and the force transducer are transmitted via connecting cables (2 for pressure, KKPC28-500; 1 for temperature, KKAPT-500; 2 for flow rate, KKHO1x1-500) and recorded in the memory of the measurement data logger. It is crucial to correctly install the flow rate transducers in accordance with the markings (arrows). The arrowhead indicates the direction of oil flow.

The procedure for measuring the impact energy and frequency of the hydraulic hammer should begin with an inspection of the measurement station prior to transportation to the test site.

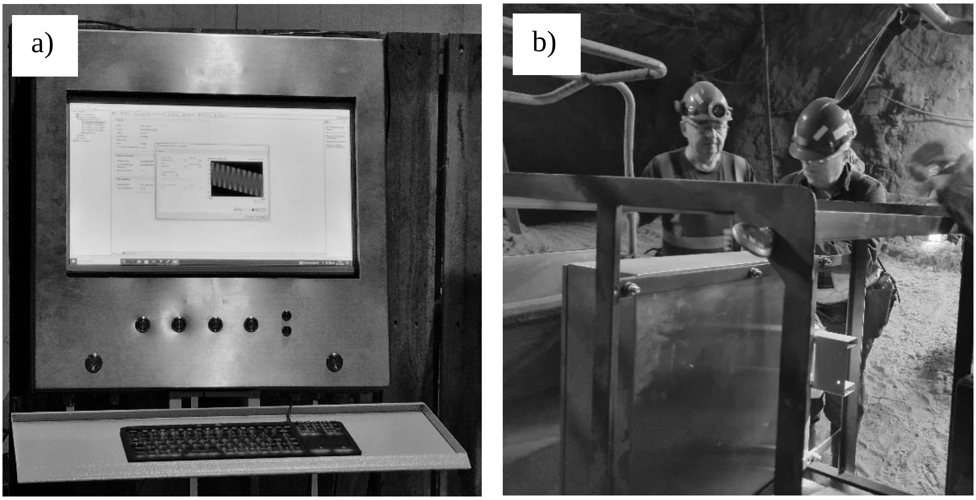

Fig. 4. Measurement recorder a) front view, b) placed on a car

Next, the entire system should be assembled and powered on to verify the readings of the data acquisition system. If no irregularities are found, the station may be transported to the test site and assembled. The first step at the test site is to install the pressure, flow, and temperature transducers (Fig. 5) and connect them to the data logger.

The energy transducer, along with the calibration system and base plate, should be placed on the grate, ensuring that the recess of the plate is properly seated within the grid opening (Fig. 3a). As before, the measurement system must be verified for correct operation. Once confirmed, the force transducer should be calibrated.

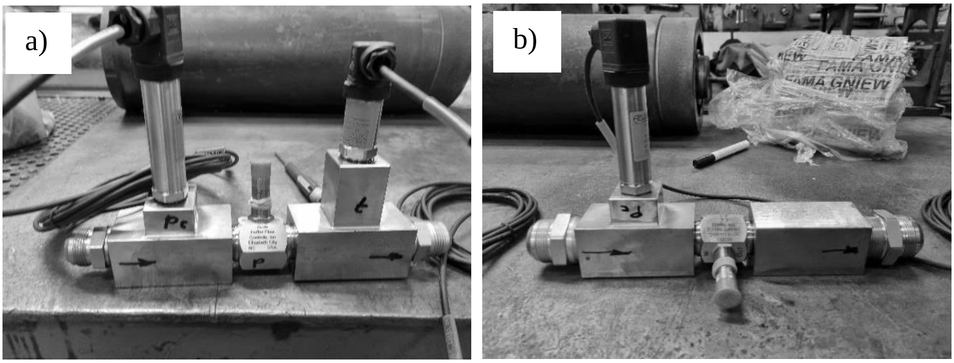

Fig. 5. Designation of transducers on the hammer’s a) supply line and b) return line: pressure sensors pz, ps flow rate sensors qp, qs and temperature sensor tz

The calibration procedure involves dropping a calibration mass from a defined height while simultaneously measuring the amplitude of the resulting force impulse. This calibration must be performed prior to each measurement campaign if the transducer base plate has been repositioned due to mounting or disassembly.

Upon completion of the calibration and determination of the transducer’s calibration constants, the measurement of impact energy and other parameters may commence. At this stage, the guide assembly must be removed. The tested hammer should then be positioned against the force transducer in such a way that the axes of the chisel and the transducer are aligned. Applying the hammer and its chisel to the transducer with the required preload should be accompanied by force registration. Once the contact is properly established, the hammer can be activated, and the impact force, along with other measured signals, can be recorded.

The testing of the hammer and the registration of the measured signals enable post-processing using specialized software to determine actual parameter values. This applies to pressure and flow rate, where mean values are calculated, and to the force and frequency of impacts. Measurement results are automatically stored in the data logger’s memory and can also be archived on data sheets (Fig. 6).

The described methodology and measurement setup provide a basis for evaluating, and testing procedure for evaluating the functional parameters of hydraulic impact hammers provides a basis for assessing the quality of these devices both at the investment stage and during operational use. Accordingly, the application of this procedure is recommended for the evaluation of hydraulic impact hammers.

4. TESTING OF HYDRAULIC IMPACT HAMMERS

Using the previously described measurement systems (method, test stands, and procedure), relevant measurements were conducted on both rotary-percussive drills and hydraulic hammers. It should be noted that the testing of rotary-percussive drills was carried out as part of internal research activities at the Department of Machinery Engineering and Transport at AGH University Krakow, which owns the aforementioned measurement station. In contrast, the hammer tests were initially conducted in cooperation with personnel from the Rudna Mining Division (O/ZG Rudna), and later as part of maintenance operations carried out by the mine, which also owns the described measurement system.

The testing of hydraulic impact hammers under the operational conditions of the Rudna Mining Division (O/ZG Rudna) is carried out using a mobile diagnostic station owned by the mine. These tests are conducted directly at the work sites of the hammers, namely at material unloading points commonly referred to as grates.

The current objective of the testing is to assess the technical condition of the hammers in use and to develop a database that enables monitoring of their technical performance over the course of their operation at O/ZG Rudna. Within this database, each hammer is assigned a record containing measurement cards (Fig. 6), maintained in the order in which the tests were performed.

The recorded test results are automatically analyzed, and an indication of the hammer's technical condition is displayed on the monitor. Based on this information, the operator conducting the test can decide whether the hammer should remain in operation or be replaced. The decision support is color-coded: green indicates continued use, yellow signals the need for operator decision, and red indicates the need for inspection or servicing.

The conducted experimental investigations confirmed that the proposed empirical method enables quantitative determination of impact energy E_u and impact frequency fu as functions of supply pressure p_z and flow rate q_z.

For the tested hydraulic hammers, the measured impact energy ranged from 1570 ÷ 1800 J, while the impact frequency varied within 5.5 ÷ 6.7 Hz, depending on the supply parameters. The observed relationships $E_u = \mathrm{f}(p_z)$ and $f_u = \mathrm{f}(q_z)$ were approximately linear within the operating range, which confirms the validity of the assumed proportionality coefficients.

The overall efficiency of the tested impact mechanisms, determined based on the measured parameters, was found to be within the range of 8.2 ÷ 17.2, with hydraulic efficiency and mechanical efficiency contributing at levels of approximately 0.07 ÷ 0.12 and 117 ÷ 140 respectively.

The application of the mobile measurement station enabled insitu diagnostics with measurement repeatability at the level of ± 5 % for impact energy and ± 4.5% for impact frequency. The calibration procedure based on energy equivalence ensured consistency of results despite variations in operating conditions.

Raport z badania hydraulicznego młota udarowego
w KGHM Polska Miedź S.A., O/ZG Rudna

Hydrauliczny młot udarowy:
typ **OCM 100**, numer kopalniany ....

Punkt przesypowy nr: .....
Data pomiaru 23.02.2025r.
Numer pomiaru: 3

Wyniki pomiarów:
siła docisku F_d – 4.6 kN
ciśnienie na zasilaniu p_z – 11.2 (6.7) MPa max(min)
natężenie cieczy na zasilaniu q_z = 81.3 (44.4) dm^3/min max(średnia)
temperatura cieczy hydraulicznej na zasilaniu t_c = 44.5 °C
ciśnienie cieczy na spływie p_s – 0.10 (0.02) MPa max(min)
natężenie cieczy na spływie q_s – 155.0 (118.4) dm^3/min
max(średnia) energia udaru E_u = 1570 J
częstotliwość udaru f_u – 5.4 Hz

Stan techniczny młota: 0.0
sprawność mechaniczna udaru, 140.1 J/MPa
sprawność hydraulina udaru, 0.123 (Hz*min)/dm^3
sprawność całkowita, 17.2 (J*Hz*min)/(MPa*dm^3)

Parametry fabryczne młota:
masa młota m_m = 1050 kg
masa bijaka m_b = 31 kg
masa grota m_g = 70 kg
średnica grota d_g = 114 mm
ciśnienie cieczy na zasilaniu p_{zf} – 14 MPa
natężenie cieczy na zasilaniu q_{zf} – 120-130 dm^3/min
energia udaru E_{uf}. = 1860 J
częstotliwość udaru f_{uf} – 6.7-8.3 Hz

Parametry wzorcowania przetwornika siły:
masa wzorcowa m_w = 45 kg
energia wzorcowa E_{uw} – 420 J
godzina (data) wzorcowania: 08:27 (23-02-25)

Nazwisko i imię osoby prowadzącej badania: ....

Fig. 6. View of the measurement card for hydraulic impact hammers

The results also demonstrated that a decrease in impact energy of more than 25% relative to reference values may indicate significant wear of internal components, providing a practical diagnostic criterion for maintenance decisions.

Furthermore, the archiving of measurement results allows for tracking changes in operational parameters over time, enabling estimation of service intervals and supporting predictive maintenance strategies.

5. SUMMARY

The developed empirical method for determining the impact energy and frequency of impact motors enables the assessment of their operational efficiency. This method can be applied to measurements conducted both on stationary and mobile test stands. It is particularly recommended for evaluating the technical condition of hydraulic impact hammers and rotary-percussive drills.

For these machines, a dedicated application of the method, an experimental procedure, and corresponding measurement stations have been developed. These are mobile stations, which facilitate their use without the need for disassembly of the hammer or drill.

The empirical method for determining impact energy and frequency of impact motors is a comparative technique; its results can be used, compared, and analyzed only when tests are conducted using the previously described stations (for hammers and drills). Naturally, the method may also be applied to other types of impact motors, provided that dedicated test stands are used for those devices.

In conclusion, the following can be concluded:

1. The developed method for assessing the technical condition of impact hammers is a comparative method.
2. The proposed mobile measurement station allows the hammer to be tested at its operating location, without the need for disassembly.
3. During testing at this station, it is required to perform measurements accurately and in accordance with the defined procedure.
4. The proposed method for assessing the technical condition of impact hammers can be used to assess other impact motors, provided that dedicated measurement stations are available.

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