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**Yu. O. Zhulai**[*1],
orcid.org/0000-0001-7477-2028,
**D. D. Zahovailova**[2],
orcid.org/0000-0002-2388-3155

1 – Institute of Transport Systems and Technologies of the National Academy of Sciences of Ukraine, Dnipro, Ukraine
2 – Communal Institution of "Chemical and Ecological lyceum", Dnipro, Ukraine
[*] Corresponding author e-mail: zhulay@westa-inter.com

# ENERGY EFFICIENT TECHNOLOGIES FOR THE MINING INDUSTRY

The cavitation generator of fluid pressure oscillations is a promising device for productivity and efficiency improvement in the mining industry (hereinafter referred to as the generator). Due to the periodic growth, separation and collapse of cavitation cavities into generator volume, shock pressure oscillations are realized with a frequency range from 1 to 20 kHz. Oscillatory pressure peak values are up by 4 times higher than the steady-state pressure at the generator inlet. The destroyed rock takes on a fatigue character under repeated alternating effects of force impulses. Due to the development of a network of microcracks in the rock, the discontinuity of the rock mass occurs at stresses lower than the rock ultimate strength. This leads to an increase in the rate of penetration, high-quality disintegration of well productive zones and an increase in their production rate, as well as to effective loosening and degassing of outburst-prone coal seams.

**Purpose.** To conduct a systematic analysis of the use of a cavitation generator in the mining industry and evaluate its effectiveness. To develop a simplified method for calculating the maximum values of the range of fluid pressure oscillations by the generator.

**Methodology.** The techniques are based on the study of recent research and publications on the use of the generator as a means of impulse action, and on the processing of on its dynamic parameters experimental data.

**Findings.** The results are given in the form of the main parameters that determine the efficiency of technological processes with hydro pulse exposure. The calculation dependences of values are presented of the cavitation parameter for which of the maximum levels of the fluid oscillation are implemented on the injection pressure and those of the maximum values of the range of fluctuations on the cavitation parameter.

**Originality.** It has been established that the use of the generator as a means of impulse action intensifies the mining industry's technological processes and leads to a significant reduction in specific energy consumption. A new simplified method for calculating the maximum level of the oscillation range has been developed, which makes it possible to determine the rational operation modes of the generator.

**Practical value.** At the stage of designing new equipment or upgrading existing equipment, this simplified method allows determining the effective mode of operation of the generator by engineering methods to reduce the specific energy consumption of the technological process.

**Keywords:** *energy-efficient technologies, cavitation generator, fluid pressure oscillations, periodically stalled cavitation, hydro pulse effect*

**Introduction.** In the context of the rapid growth of energy prices, much attention is paid to the development of energy-saving technologies and energy-efficient devices. Unfortunately, the Ukrainian economy consumes energy resources by several times more (per unit of production) compared to industrial countries. In the past years, there has been a steady world trend in the development of technologies based on the use of periodically disruptive cavitational flows. This contributes to the intensification of production processes and energy efficiency. The relevance, social and economic significance of such research is due to the need to develop economically profitable technologies and meets the priority areas for the development of science and technology in Ukraine.

A promising device in the development of this direction is the Venturi tube of special geometry, which creates high-level amplitude oscillations in the range of sound frequencies. It was developed at the Institute of Technical Mechanics of the National Academy of Sciences of Ukraine (ITM NASU) and was called the 'cavitation generator of fluid pressure oscillations' ((hereinafter referred to as the generator). Converting the stationary fluid flow into a pulsating flow, the generator realizes a large discrete power in the pulse in the output pipeline. The generator is easy to manufacture and there are no moving parts, no transmission of water pressure oscillations to the pump. It works only on the energy of the process fluid and fits seamlessly into existing equipment.

**Literature review.** The main results of the experimental study on the physical processes occurring in the flow channel of the generator were obtained in the ITM NASU and SSAU (Pilipenko V. V., 1989). It is established that the most developed oscillations are observed in a hydraulic system with a generator at the values of the diffuser opening angle greater than 16°.

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The design schematics of the generator and its installation in the device of hydropulse action are presented in Fig. 1.

Subsequently, the cavitation generator *1* with the last hydraulic channel *5* was called the hydrovibrator. The presence of such a hydraulic channel is especially important to eliminate the loss of pulse energy when the generator operates in a flooded jet of liquid.

The cavitation generator operation mode is characterized by the following parameters:

- geometric parameters: $d_{cr}$ and $l_{cr}$ are the diameter and length of the critical cross-section; $\beta$ is the angle of the diffuser disclosure; $D$ and $l_d$ are the output diameter of the diffuser and its length;
- regime parameters: $P_1$, $P_2$ and $Q$ are full inlet and retaining pressure and fluid flow rate through the generator; $\tau$ is a parameter of the mode of fluid cavitation flow;
- basic dynamic parameters: $f$ is the frequency of self-oscillations; $\Delta P$ is the range (peak to peak values) of fluid pressure self-oscillations. Due to the inharmonic oscillations shape the $\Delta P$ is $P_{2max} - P_{2min}$, where $P_{2max}$ is the maximum value of the pressure in the pulse; $P_{2min}$ is the minimum pulse pressure.

The cavitation parameter $\tau$ in this case is the ratio of pressure, under the action of which the cavern collapses to the pressure that realizes the velocity head in the critical cross-section, under the influence of which the cavern arises and grows

$$\tau = \frac{P_2}{P_1}. \quad (1)$$

As an example, Fig. 2 shows the time dependence of the pressure $P_2$ in the hydraulic channel at the output of the generator ($d_{cr} = 6$ mm, $\beta = 20°$, $D = 24$ mm) and the chronophotography of the development of periodically disruptive flow in the channel. The arrow indicates the direction of the current. At the same time, the discharge and support pressures were $P_1 = 10$ and $P_2 = 2.0$ MPa.

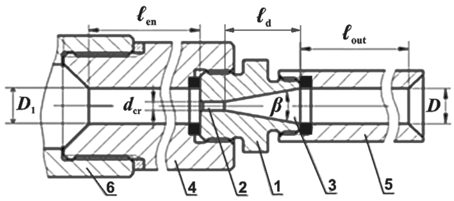


*Fig. 1. Design schematics of the cavitation generator and its installation in the hydropulse device:*

*1 – generator; 2 – critical cross-section; 3 – diffuser; 4 – inlet channel; 5 – last-diffuse hydraulic channel; 6 – feedline pipe; $l_d$, $l_{en}$, $l_{out}$ – lengths of the diffuser, inlet, and post-diffuser channels*

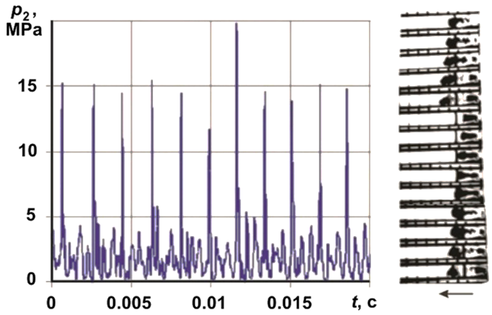


*Fig. 2. Waveform of pressure recording $p_2$ and the chronophotography of the process in time at the generator outlet for $\tau \approx 0.2$*

The process waveform indicates that the generator converts the stationary flow of the liquid into a pulsating flow. It can be seen from the chronophotography that the cavitation cavern occurs in the critical cross-section of the generator located on the right side of the chronophotography. Then it goes into the diffuser and when it reaches the maximum length, cavern breaks off, sweeps down the stream and in the zone of high pressure is slammed into the hydraulic channel behind the generator. The cross-section of the cavern separation corresponds to the transition of the cylindrical section of the generator into the diffuser. The instrumental measurements established the drop in local static pressure in the critical cross-section of the generator to being close to the pressure of fluid saturated vapors. This leads to the rupture of the fluid continuity and the formation of a cavern filled with vapors and gases.

The process of detachment and collapse of part of the cavern occurs strictly periodically, that is, with a stable frequency of several hundred Hz. This leads to the conclusion that the abnormally high periodic pressure pulses in the hydraulic channel behind the generator are conditioned by the mode of periodic-disruption cavitation.

Fig. 3 presents the calculated dependencies of the scale of cavitation oscillations *DP* at the output of the generator on the cavitation parameter τ and experimental data obtained during bench tests (Zhulai Yu. A., 2017).

Calculated and experimental data are given for generators with $d_{cr}$ equal to 8, 6, 4 and 2.5 mm. The values of the input pressures were $P_1$ = 1, 5, 15 and 25 MPa. The location of the experimental points relative to the theoretical dependencies of the oscillation span at the output of the generator $\Delta P$ on the cavitation parameter τ shows their satisfactory convergence. The relative error of the results does not exceed 15 %.

With a fixed value τ, an increase in the pressure at the inlet to the experimental sample of the generator $P_1$ leads to an increase in the magnitude of the range of pressure fluctuations $\Delta P$. The nature of the established dependencies shows that with all the values of pressure $P_1$, the range $\Delta P$ of the oscillatory value of pressure with an increase in τ first increases sharply, reaching the maximum value, and in the future, at a certain value τ decreases.

The dependences $\Delta P(\tau)$ for different pressure values $P_1$ have a maximum in the range of changes in the cavitation parameter $\tau \approx 0.15$–$0.3$. With an increase in the discharge pressure $P_1$, the maximum $\Delta P$ shifts towards smaller values of the cavitation parameter τ.

The maximum value of the range $\Delta P$ of the oscillatory value of the pressure is about from 1.4 to 3.5 times higher than the pressure at the inlet to the generator $P_1$. At the same time, with an increase in pressure of the injection $P_1$ ratio $\Delta P/P_1$ decreases. Thus, at $P_1$ = 1 MPa $\Delta P/P_1 \approx 3.5$, at $P_1$ = 25 MPa $\Delta P/P_1 \approx 1.4$.

The analysis of the dependencies presented in Fig. 3 clearly shows that the range of the oscillatory pressure value $\Delta P$ is determined by the injection pressure of the liquid $P_1$ and the cavitation parameter τ. The volumetric flow rate of the liquid (determined by $d_{cr}$) has no effect on the value $\Delta P$. According to the results of the study (Zhulai Yu. A., 2017), it was established "that the amount of pressure that occurs when the cavern collapses does not depend on its size, but is determined by the speed of movement of the cavern wall".

Fig. 4 presents experimental and calculated dependencies of the frequency of self-excitation impulsions *f* on the cavitation parameter τ (Zhulai Yu. A., Voroshilov A. S., 2015).

The dependencies are linear. It can be seen that over the entire range of variation of the cavitation parameter τ the calculated and experimental values of the frequency *f* are satisfactorily consistent. The relative error for all generators does not exceed 7 %. An increase in the pressure at the inlet to the generator $P_1$, as well as a decrease in the radius of the critical cross-section of the $d_{cr}$ generator, leads to an increase in the frequency *f* of oscillations.

In the works by academician Pilipenko V. V. the examples of practical application of the generator in technological processes of metallurgy, mechanical engineering and chemical industry are given. Here, positive results were achieved in intensification and resource saving. The use of a generator in these cases allowed reducing specific energy consumption from 20 to 50 %.

At the same time, the work on the use of the generator in the mining industry is not properly systematized. This makes it

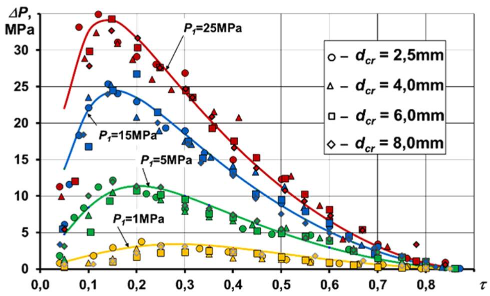


*Fig. 3. Theoretical and experimental dependencies of the range $\Delta P$ on the cavitation parameter τ for the inlet pressure $P_1$ changes from 1 to 25 MPa*

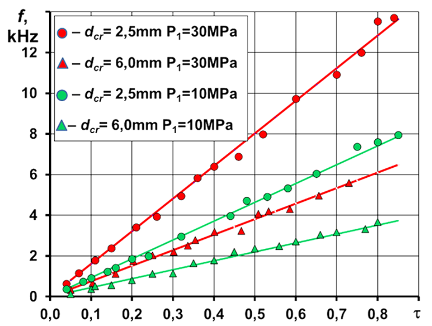


*Fig. 4. Theoretical and experimental dependencies of pulse self-excitation frequency f on cavitation parameter τ*

difficult for specialists to assess the energy efficiency of a particular technological process.

In the indicated examples of the use of the generator, its adjustment to the maximum levels of the range of cavitation oscillations was carried out according to the experimental data obtained during bench tests, which entailed additional material costs.

When reconstructing or creating a fundamentally new type of equipment using the generator to intensify technological processes, the development and application of methods for theoretical forecasting of the parameters of working processes in the installation is of great importance. These methods should be reliable, but at the same time simple enough. They should allow engineering methods to assess the hydropulse effect in a particular process.

**The purpose of the work.** Systematization of examples of the use of a cavitation generator in technological processes of the mining industry, as well as assessment of their energy efficiency. Development of a simplified method for calculating the maximum values of the ranges of fluid pressure oscillations implemented by the generator.

***Systematization of examples of the use of the generator in the mining industry***. There is known research and developments aimed at the use of the generator in technological processes in the mining industry:

- when drilling a well, spreading the diameter of casing pipes by creating a vibration load on an actuator [1];
- splitting of the productive zones of water formations due to the high-frequency alternating effect of the liquid on the capillaries of the rock, the solid phase and the filtrate [2];
- creation of new technical means of combating gas-dynamic phenomena in mines by hydropulse loosening of emission-hazardous coal seams [3].

***Drilling projectile with cavitation hydraulic vibrator***. To speed up drilling operations, since 1901 submersible impact vehicles have been used. Their complex design of moving parts, springs and rubber cuffs significantly shortens their service life. Still, the efficiency of hydraulic shocks does not exceed 10 % [4]. Hydraulic shock systems of volumetric type, by reducing hydraulic losses, make it possible to increase the efficiency up to 20 %. However, it should be noted that work to improve the characteristics of hydraulic shocks is currently continuing in almost all countries engaged in drilling.

Over the past decade, the Russian Federation has been continuing research aimed at studying the low-frequency vibrations of drilling tools, and volumetric hydraulic shock machines have been developed. Their peculiarity lies in the presence of a network pressure accumulator. This complicates the design of volumetric water hammer machines and limits their capabilities, especially at significant drilling depths [5].

The new direction in the development of submersible impact vehicles created by ITM NASU together with SKB Geotechnica eliminates the shortcomings of hydraulic shocks. This was realized in the development of a drilling projectile with a cavitation hydraulic vibrator. The correctness of the choice of the proposed direction is confirmed by the works of researchers from the USA, Canada and China, where methods for forecasting and optimizing the technological parameters of drilling are developing in [6]. In China, a new drilling tool has been developed that generates cavitation processes by interrupting the jet and then amplifying them in a resonance chamber.

The layout of the drilling rig structure developed at ITM NASU and a photograph of the hydraulic vibrator are presented in Fig. 5. As can be seen from the figure presented, the drilling rig does not feature the main disadvantages of submersible hydraulic shockers. It does not have moving parts, and, unlike volumetric type hydraulic shockers, it does not require additional energy sources.

The drilling rig is easy to manufacture and fits seamlessly into existing equipment. It does n ot affect the pump, since pressure oscillations above the place of its installation are not transmitted.

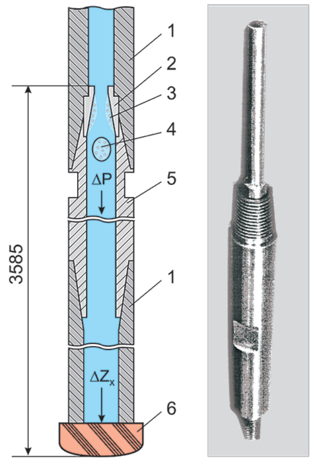


*Fig. 5. Layout of the drilling rig structure and photo of the hydraulic vibrator:*

*1 – drill pipe; 2 – generator; 3, 4 – cavern saddled and its part that has broken off; 5 – hydraulic vibrator; 6 – rock-destroying tool*

The drill projectile works as follows. The flushing fluid enters through the drill pipe *1* to the inlet of the generator *2*. Due to an increase in the speed of the liquid in the critical cross-section of the generator, there are breaks in the continuity of the liquid and a cavity *3* is formed, filled with vapors and gases. When the cavern reaches a certain size, it is torn off and demolished into a zone of high pressure. The detached part of the cavern *4* collapses in the hydraulic channel of the hydraulic vibrator *5*.

Thus, using the energy of the washing fluid, the hydraulic vibrator converts the stationary flow into a discrete-pulsed one. At the same time, high-frequency shock pressure oscillations $\Delta P$ are implemented. They are transformed into longitudinal vibration accelerations $\Delta Z$ on the rock-destroying tool *6*.

Drilling projectiles with a cavitation hydraulic vibrator underwent a full range of experimental studies at the hydrohalic and drilling stands of the Geotechnica Design Bureau in Podolsk.

As an example, Fig. 6 shows the results of testing a drilling rig in a well at a depth of 87 m [7]. The rock to be destroyed is granite. At the same time, the length of the drilling projectile was $l$ = 3,585 mm, and the diameter of the critical cross-section of the generator $d_{cr}$ = 6 mm. Tests were carried out at the injection pressure $P_d$ = 4 MPa, the flow rate of the washing fluid is $Q$ = 2,4L/s and axial load is $F$ = 9,8 kN.

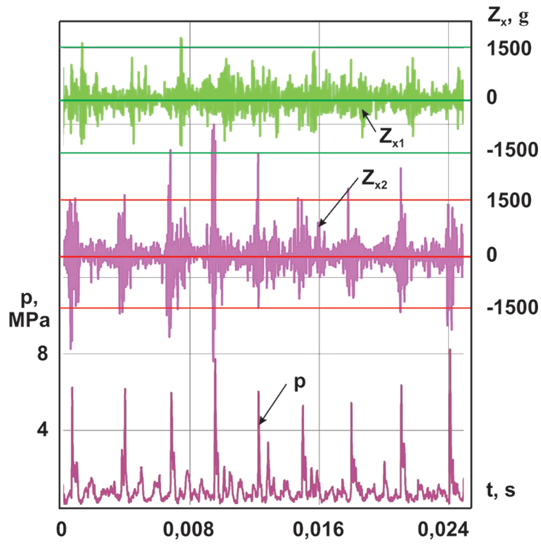


*Fig. 6. The waveform recording of dynamic parameters during testing of the experimental sample of the drilling string during it is immersed in a well* [7]

The results of this test confirm the presence of dynamic process determined by the hydrovibrator operation mode of periodic cavitation. Pressure oscillations $p$ in the flow channel of the hydrovibrator are characterized by an impact shape with peak values from 5 to 8 MPa and a dominant frequency of 374 Hz. These oscillations are converted into vibration accelerations on a rock-destroying instrument with average values of $\Delta Z_x \approx 3{,}200$ g. The dominant frequency of longitudinal vibration accelerations is superimposed on the frequency of the constituent elements of the drilling rig structure (curves $Z_{x1}$ and $Z_{x2}$ on Fig. 6).

The pilot tests have confirmed its effectiveness in the construction of wells with a diameter and depth of ≈ 600 and 190 mm in the region of Astana (Dzoz N. A., 2008). An increase in drilling speed was established by 71.5 % compared to the rotary method and by 30 % compared to hydraulic shocks. The resource of the rock-breaking tool increased by about 30 with a 40 % reduction in energy consumption.

**Expansion of the diameter of casing pipes.** One of the difficult tasks in the construction of production wells for the extraction of liquid and gaseous minerals is the sealing of the wellhead. For deep-water fields, this labor-intensive operation was carried out by lowering the equipment to depths of 1,000 m or more, followed by the injection of special cement mortars. Since 2000, western firms have been using a hydraulic method for sealing to expand the diameter of casing pipes in the wellhead area.

The world leader in expanding equipment for sealing wells using strong sliding products is "Weatherfopd" company. Its equipment expands casing pipes by supplying a high-pressure flow of liquid under the expansion cone. These products provide unique solutions for sealing the wellhead, isolating the problem layer during drilling and repairing casing. To reduce friction, which consumes approximately 50 % of the energy of the liquid, a special lubricant MSDS with molybdenum additives was used, which leads to significant economic costs.

It is possible to reduce friction by imposing vibrations on the expansion cone, in the flowing part of which a generator is mounted (Dzenzersky V. A. and Zhulai Yu. A., 2011). Tests of such a device with a critical section of the generator $d_{cr}$ = = 1.4 mm were carried out on samples of certified steel pipes with an outer diameter of 133 mm and a wall thickness of 6 mm.

As an example, Fig. 7 shows the time dependence of the increase in the average pressure in the chamber before the expansion cone $P_2$ (left axis) and the axial vibration $Z$ (right axis) realized on the cone when it comes into contact with the expandable pipe. From the presented data it can be seen that vibration accelerations on this design are implemented with a range of ≈ 2,000 g and a frequency of $f$ from 3 to 10 kHz in the range of change $P_2$ from 8 to 20 MPa ($\tau$ = 0.2–0.5).

The outer diameter of the pipe after expansion increased by 17 % and amounted to 150.6 mm with a wall thickness of 5.7 mm, while its ellipse content does not exceed 0.4 mm. No cone has been detected after all tests.

As a result of the experimental work performed, it was found that the use of the hydropulse method of pipe expansion reduces friction resistance by 93 % compared to static expansion and reduces energy costs by 40 %.

***Restoration of the flow rate of water wells.*** An example of the successful use of a cavitation hydrovibrator is the initiation of water wells [2].

The efficiency of aquifer operation is estimated by the flow rate of the well. According to its value, the filtration properties of the reservoir are evaluated. A decrease in the flow rate of the well is observed when it silts, overgrowth of the cross-section of the pipes and the inner surface of the filter due to the deposition of various mineralized sediments in them. Technical measures related to the processes of restoring the flow rate of the well include mechanical cleaning with metal ruffs and scraper devices, vibration effect on the column with a filter, the electric pulse method, various methods of washing, etc. Technical hydrochloric acid is still used to restore the flow rate of wells. As a result of its reaction with calmating compounds, dissolved salts, water and gaseous products are formed.

However, the technological capabilities of these measures do not make it possible to use the equipment of wells (submersible pump, water lifting pipes, and others). Technical means for splitting are not unified, and the use of acid causes a harmful effect on the environment.

These disadvantages determine the advantages of the hydropulse method of exposure to increase the filtration properties of productive formations. When elastic oscillations are excited in a porous medium in the productive aquifer zone, there is a violation of the continuity and the formation of a network of microcracks in layers of clays and growths. There is a destruction of mineralized deposits in the pipes and on the surface of the filter. Their removal is carried out under the influence of sharp fluctuations in the speed of water in the filter, the filter zone and in the casing pipes.

Determination of the efficiency of using a cavitation hydraulic vibrator with a critical cross-section diameter of the generator of 8 mm was carried out on two hydrogeological wells with a diameter of 400 mm (Dzoz N. A., 2008).

As an example, Fig. 8 shows the schematic of the installation of a hydraulic vibrator and water lifting equipment during the splitting of wells.

During the tests of the hydraulic vibrator, the water level was determined by a static pressure sensor placed on the water lifting pipe behind the submersible pump. The values of the pressure pulses were measured by a pulsation sensor located directly in front of the hydrovibrator. It was found that in the

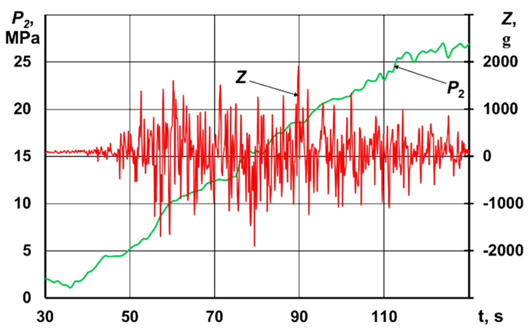


*Fig. 7. Time change in the pressure in the chamber before the expansion cone and its axial vibration acceleration*

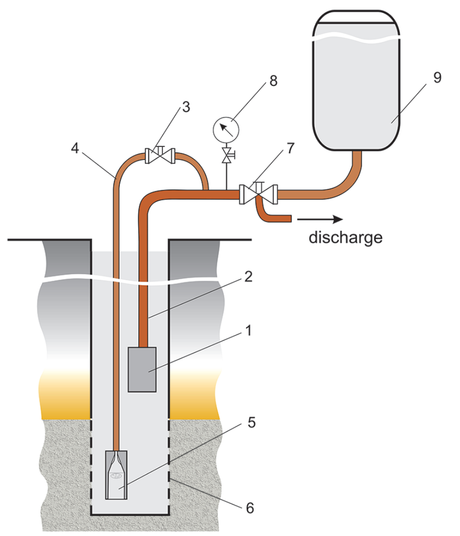


*Fig. 8. Schematics of installation of the hydraulic vibrator and water lifting equipment during splitting of wells:*

*1 – submersible pump; 2 – water lifting pipe: 3 – valve; 4 – flexible hose; 5 – hydraulic vibrator; 6 – product area filter; 7 – three-way crane; 8 – pressure gauge; 9 – water tower* range of pressure change at the inlet to the hydraulic vibrator from 1.0 to 4.0 MPa and water flow rates from 2 to 5 l/s, pressure pulses from 3.5 to 12.0 MPa with a frequency of their repetition from 200 to 1,400 Hz are realized in the well.

According to the above schematics, two wells were restored. Comparison of the efficiency of well splitting was carried out before and after its processing by changing the flow rate.

Initially, the well was treated in the mode of inflow of all water to the hydraulic vibrator with the three-way tap *7* closed and the valve *3* open. The flow rate was increased by 40 %. After cleaning the well from sludge particles by submersible water pump for draining (valve *3* is closed, three-way tap *7* is opened for drain), switched to the second mode. During the operation of the submersible pump, the hydraulic vibrator worked simultaneously and water was extracted for 68 hours. The amount of liquid supplied to the generator was adjusted according to the pressure gauge readings.

It was found that during hydrodynamic treatment, the average reservoir opening pressure is by 2–2.5 times lower than that with static hydraulic fracturing. The increase in well flow rate was 200 % compared to the design flow rate.

***Combating sudden emissions in coal mines.*** Analysis of the means of combating gas and dust factors in countries with a developed coal industry shows that the injection of liquid in static mode into coal seams is a fundamental measure. Due to the preliminary humidification of the coal massif, this allows reducing dust formation and the intensity of gas production during the destruction of coal.

However, the deterioration of mining and geological conditions associated with an increase in the depth of development of gas-abundant coal seams led to a significant decrease in the effectiveness of this measure.

In the presence of rocks prone to soaking, and the formation of unloading zones in front of the face, pressure injection leads to a breakthrough of the liquid into the face. This does not allow pumping the required amount of liquid into the reservoir and creating a uniform degassed zone around the well, provided for by regulatory documents. Sudden emissions, explosions of methane and coal dust lead to catastrophic consequences. In this regard, the creation of safe conditions for mining operations on the gas factor is the most relevant in the coal industry.

The importance of methane recovery from coal seams is confirmed in all countries, including the United States, China, Australia, India and Russia. For example, in the work [8], the extraction of methane is proposed to be carried out by injections into the coal seam of $CO_2$. But this technology of methane extraction is quite complex and energy-consuming.

One of the promising areas to improve the quality of hydro-loosening is the creation of hydrodynamic pulses in the well behind the cavitation hydrovibrator and their conversion into mechanical vibro-loading of the coal seam [9]. The effectiveness of the hydropulse effect on the coal massif is primarily characterized by the development of a crack system, which is determined by the ratio of the strength characteristics of coal and the energy characteristics of the injected liquid.

In recent years, significant results in this direction have been obtained by the Institute of Geotechnical Mechanics (IGTM) of the National Academy of Sciences of Ukraine together with PJSC Krasnodonvuhillia. A method of hydropulse loosening of emission-hazardous coal seams has been developed here [3]. A significant amount of laboratory research has been carried out to substantiate the geometric and operating parameters of the device implementing this method.

The results of bench tests and the conclusions obtained from them made it possible to proceed to mining and experimental work to assess the effectiveness of the hydropulse ripping device in industrial conditions and compare the results obtained with static injection. The scheme of the device and its placement in the well is shown in Fig. 9.

The device works as follows: a high-pressure flow of water through the liquid flow distributor *3* and the tee *5* enters the inlet of a hydraulic vibrator consisting of a generator *6* and a hydraulic channel *5*. The generator converts the static flow of the liquid into a pulsating flow. It propagates through the hydraulic channel *7* to the filtration part of well *8* and is transmitted to the coal array.

The generator converts the static flow of the liquid into a pulsating flow. It propagates through the hydraulic channel *7* to the filtration part of well *8* and is transmitted to the coal array. The pulse repetition frequency lies in the range from 1 to 7 kHz. Shock self-oscillations of pressure, reducing the internal and contact friction of coal, initiate the development of shear deformation and cracking in multi-inclined planes. It was found that the hydropulse effect leads to a significant reduction in the time of the active process of loosening the coal seam [10]. At the same time, the quality of loosening increases significantly.

Evaluation of the efficiency of hydraulic fracturing was carried out by analyzing the acoustic signal of the ZUA-98 control equipment. The modes of hydropulse loosening of the coal seam [11] have been established: the initial one – complete filling of the well with water and increasing the pressure of the support in it; active stage of hydropulse loosening – at a steady pressure of liquid support (according to the manometer *5*); completion of the active stage – when the pressure of the liquid support in the filtration part of the well drops at the level of 30–50 %. After the completion of the active cracking process, hydropulse loosening becomes ineffective. Digitization of the seismogram of the registration of the active stage of hydropulse loosening of the reservoir by the ZUA-98 equipment is shown in Fig. 10.

As can be seen from the above seismogram, the active stage of hydropulse loosening of the coal seam is accompanied by intensive development of coal cracks.

Comparative analysis of the results of loosening by the hydropulse method and normative – static injection showed that:

- in relation to static injection, the time of hydropulse loosening is reduced by more than 35 %, and the volume of pumped liquid by 40 %, which led to a decrease in energy consumption by about half;
- with static injection after 15 minutes, a breakthrough of water into the face occurred along the coal layer, as a result of which, the hydraulic fracturing of the seam was stopped;

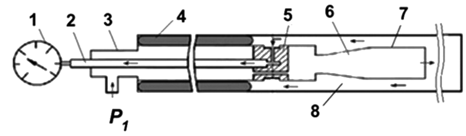


*Fig. 9. Schematics of the device for hydropulse loosening of corner layers:*

*1 – pressure gauge; 2 – support pressure measuring channel; 3 – liquid flow separator; 4 – sealant; 5 – tee; 6 – generator with $d_{cr}$ = = 2.5 mm; 7 – hydraulic channel; 8 – filtration part of the well*

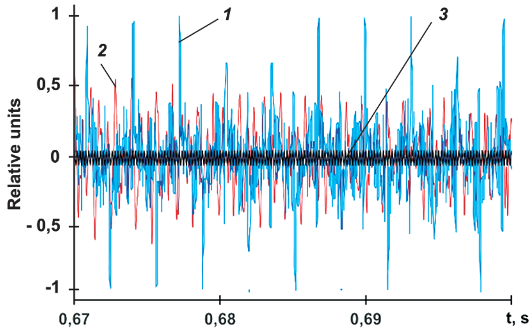


*Fig. 10. Digitization of the seismogram of the active stage of hydropulse loosening of the coal seam:*

*1 – levels of the signalogram of crack development; 2 – acoustic signal levels of the operating range of hydropulse ripping: 3 – acoustic signal level of the pump unit*

- with pulse injection, the release of fluid in the face of the production was not observed. At the end of the process, a variety of grindings and abundant dripping were displayed over the face area. This characterizes the quality of hydro-loosening and the moisture of the coal seam;

- the specific gas emission through adjacent wells increases by about 2 times per meter of the exposed surface of coal compared to static injection;

- after hydropulse loosening, there is an increase in the rate of coal production.

***Development of a simplified method for calculating the maximum values of the ranges of fluid pressure fluctuations implemented by the generator***. In the above examples, the adjustment of the generator to the maximum levels of the swing of cavitation oscillations was carried out according to experimental data obtained during bench tests, which entailed additional material costs.

When reconstructing or creating a fundamentally new type of equipment using a cavitation generator for the intensification of various technological processes, the development and application of methods for theoretical forecasting of the parameters of work processes in the installation is of great importance. These methods should be reliable, but at the same time quite simple.

Analysis of mathematical methods for describing the hydrodynamic process of periodically disruptive cavitation flow of liquid in the 'generator – output pipeline' system and the results of calculations on them was performed in the work [12] and showed that:

- linear mathematical model of the generator (Pilipenko V.V., 1989) and its subsequent refinement (Zhulai Yu.A., 2017) makes it possible to obtain a quantitative reconciliation of experimental and theoretical dependencies of the scope on the cavitation parameter in the entire range of its change (Fig. 3);

- a mathematical model, in which finite element discretization of the generator structure and the output pipeline is carried out, allows taking into account the dynamic interaction of fluid vibrations and the structure with the detection of resonant oscillation modes. However, it requires some adjustment in terms of describing the basic dependencies of the dynamics of the cavitation flow in the generator if it is necessary to more carefully coordinate with the experimental data.

Calculations according to the thermodynamic model, using the classical Rayleigh-Plesset equation, solved by the method of finite Euler differences of the first order [9] are complex. The values of cavitational shocks determined by it are overestimated, and lie in the range from 800 to 2,700 MPa.

In the work [13] on a dynamic model, a quantitative assessment of the intensity of cavern collapse under various hydraulic flow conditions was performed. The results obtained are satisfactorily consistent with the experimental data.

These models are convenient when conducting research in the presence of a certain amount of experimental data, but their use for engineering calculations causes certain difficulties in terms of programming and the duration of preparation for calculations.

In connection with the above, it became necessary to develop a simplified method for calculating the maximum values of the fluctuations of the liquid implemented by the generator in the process pipeline behind it.

To achieve this goal, the following tasks were solved:

- collection of information on experimental test data of generators with different diameters of critical cross-section $d_{cr}$;

- processing of experimental data and identification of operating modes of generators, on which the maximum levels of their impulse action are implemented;

- establishment of simplified dependencies of the highest levels of impulse action of generators on the mode of their operation.

To develop a simplified method for calculating the maximum levels of pulse action, experimental data from generators with *a* $d_{cr}$ of 14 mm (used when removing the scale during hot rolling of metal), 8, 6 and 4 mm [1, 2] and 2.5 mm [3] were used. Data on the maximum values of the magnitudes of the vibrational pressure value $\Delta P_{max}$ of these generators are given in the Table.

They were processed by the Excel program, which made it possible to obtain the dependencies of the cavitation parameter τ, in which the maximum values of the range of oscillations from the pressure of the injection of the fluid $P_1$ and the maximum values of the swings of $\Delta P_{max}$ from the cavitation parameter τ are realized. This made it possible to determine their approximated equations with a high degree of probability.

Fig. 11 shows the dependence of the cavitation parameter τ (at which $\Delta P_{max}$ is realized) on the pressure at the inlet to the generator $P_1$. Here is the approximation equation of the trend line, which is a logarithmic function with a probability value of 0.9988.

The dependence of the maximum values of the swings $\Delta P_{max}$ on the cavitation parameter τ is shown in Fig. 12. Its trendline approximation equation is an exponential function with a probability value of 0.9998.

*Table*

The results of determining the maximum *of* $\Delta P_{max}$ ranges of oscillations, realized by generators with different diameters of the critical cross-section

| Mode Options | | Critical cross-section diameter | | | | |
|---|---|---|---|---|---|---|
| | | 14 mm | 8 mm | 6 mm | 4 mm | 2.5 mm |
| $P_1$, MPa | τ | *Values of* $\Delta P_{max}$, MPa | | | | |
| 1.0 | 0.284 | 3.49 | 3.58 | 3.11 | 3.39 | 3.14 |
| 5.0 | 0.203 | 11.71 | 10.93 | 11.62 | 11.39 | 11.02 |
| 10.0 | 0.169 | 18.19 | 19.01 | 17.43 | 18.52 | 18.82 |
| 15.0 | 0.152 | 25.23 | 24.01 | 24.91 | 24.41 | 25.11 |
| 20.0 | 0.139 | 29.07 | 31.17 | 28.57 | 29.57 | 30.03 |
| 25.0 | 0.13 | 35.13 | 34.92 | 32.91 | 34.24 | 33.06 |
| 30.0 | 0.121 | 39.15 | 40.22 | 37.84 | 38.56 | 38.03 |

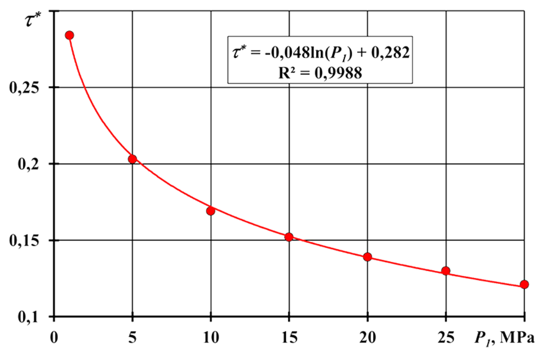


*Fig. 11. Dependence of the cavitation parameter τ, at which* $\Delta P_{max}$ *are realized on the steady-state pressure at the inlet to the generator* $P_1$

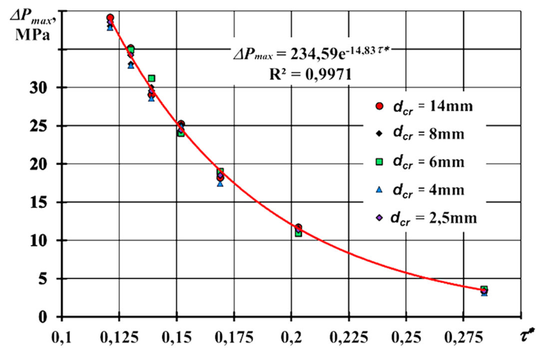


*Fig. 12. Dependence of the maximum values of the swings* $\Delta P_{max}$ *on the cavitation parameter* τ

The established approximation equations

$$\tau^* = -0.0481\ \ln(P_1) + 0.282, \quad R^2 = 0.9988; \qquad (2)$$

$$\Delta P_{\max} = 234{,}59e^{-14{,}83\tau^*}, \quad R^2 = 0.9998, \qquad (3)$$

are convenient to be applied when using shock cavitation self-oscillations with their maximum range level to increase the efficiency of various technological processes. When creating new equipment or reconstructing existing equipment, by the pressure at the inlet to the generator $P_1$ provided by the pumping unit, according to (2), the cavitation parameter τ is determined, at which the maximum value of the strokes $\Delta P_{max}$ is realized. The value of the swing value $\Delta P_{\max}$, implemented by the generator in the process pipeline, is determined in accordance with (3). For example, at the pressure at the inlet to the generator $P_1$ = 16 MPa, the value of the cavitation parameter at which $P_{\max}$ is realized is 0.15 (Fig. 11), and the magnitude of the pressure pulse will be 25 MPa (Fig. 12).

**Conclusions.** The systematization of examples of the use of the cavitation generator carried out in this work showed that it:

- allows you to intensify the technological processes of the mining industry with high quality of the work carried out;
- provides a reduction in energy consumption from 20 to 50 %.

The developed new simplified method for calculating the maximum level of the range of fluid vibrations implemented by a cavitation generator is of great practical importance. It allows one, at the stage of designing new equipment or upgrading existing engineering methods, to determine the rational operation mode of the generator to increase the energy efficiency of the technological process.

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## Енергоефективні технології для гірничодобувної галузі

*Ю. О. Жулай**[1], *Д. Д. Заговайлова*[2]

1 – Інститут транспортних систем і технологій Національної академії наук України, м. Дніпро, Україна

2 – Комунальний навчальний заклад «Хіміко-екологічний ліцей», м. Дніпро, Україна

* Автор-кореспондент e-mail: zhulay@westa-inter.com

Перспективним пристроєм, що підвищує енергоефективність технологічних процесів у гірничодобувній галузі, є кавітаційний генератор коливання тиску рідини (далі генератор). У ньому, унаслідок періодичного зростання, відриву та схлопування кавітаційних порожнин, реалізуються ударні коливання із частотами 1–20 кГц. Пікові значення коливальної величини тиску до 4 разів перевищують тиск на вході в генератор. При багаторазовому знакозмінному впливі силових імпульсів порода, що руйнується, набуває втомного характеру. Унаслідок розвитку в породі мережі мікротріщин, порушення суцільності гірського масиву відбувається при напругах, менших межі міцності породи. Це призводить до підвищення швидкості буріння, якісної розкольматації продуктивних зон свердловин і збільшення їх дебіту, а також ефективного розпушування й дегазації викидонебезпечних вугільних пластів.

**Мета.** Проведення системного аналізу використання кавітаційного генератора в гірничодобувній галузі та оцінка його ефективності. Розробка спрощеного способу розрахунку максимальних значень розмахів коливань тиску рідини, що реалізуються генератором.

**Методика.** Базується на вивченні останніх досліджень і публікацій із використання генератора як засобу імпульсного впливу та обробці експериментальних даних його динамічних параметрів.

**Результати.** Наведені у вигляді основних параметрів, що визначають ефективність технологічних процесів при гідроімпульсному впливі. Надані розрахункові залежності значень параметра кавітації, за якого реалізуються максимальні рівні розмаху коливань рідини, від тиску нагнітання й максимальних значень розмахів коливань від параметра кавітації.

**Наукова новизна.** Встановлено, що застосування генератора як засобу імпульсного впливу, інтенсифікує технологічні процеси гірничодобувної галузі та призводить до значного зниження питомих енерговитрат. Розроблено новий спрощений спосіб розрахунку максимального рівня розмаху коливань, що дозволяє визначити раціональний режим роботи генератора.

**Практична значимість.** Полягає в тому, що зазначений спрощений спосіб дозволяє на стадії проектування нового обладнання або модернізації існуючого інженерними методами визначати ефективний режим роботи генератора для зменшення питомих енерговитрат технологічного процесу.

**Ключові слова:** *енергоефективні технології, кавітаційний генератор, коливання тиску рідини, періодично зривна кавітація, гідроімпульсний вплив*

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