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EVALUATION OF THE CAVITATION GENERATOR EFFICIENCY IN THE HYDRO IMPULSIVE LOOSENING OF A COAL-BED

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ОЦІНКА ЕФЕКТИВНОСТІ РОБОТИ КАВІТАЦІЙНОГО ГЕНЕРАТОРА ПРИ ГІДРОІМПУЛЬСНОМУ РОЗПУШУВАННІ ВУГІЛЬНОГО ПЛАСТА

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ОЦЕНКА ЭФФЕКТИВНОСТИ РАБОТЫ КАВИТАЦИОННОГО ГЕНЕРАТОРА ПРИ ГИДРОИМПУЛЬСНОМ РЫХЛЕНИИ УГОЛЬНОГО ПЛАСТА

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Annotation. The paper presents the results of mining and experimental work, bench tests and theoretical studies of the energy characteristics of the stationary and pulsating fluid flow, which allow to estimate the efficiency of the cavitation generator in the hydro impulsive loosening of an outburst-prone coal-bed. The generator is the Venturi tube of special geometry in the flow part of which high-frequency self-oscillations of fluid pressure occur. The advantage of this device is the absence of additional energy sources and moving mechanical parts. Generator is installed in the filtrational part of the well. That's why all energy of cavitational self-oscillations is spent to hydro impulsive loosening of a coal-bed. The active stage of the hydro impulsive loosening and the effective range of the amplitude-frequency (AF) spectrum of the generator operation acoustic signal have been established by the AF spectrum of the sound accompaniment of the hydro impulse impact and the backup pressure of the liquid in the well. The active stage of hydro impulsive loosening of the bed occurs within 6-7 minutes at the backup pressure of the liquid in the well from 1.2 MPa to 7.5 MPa. The frequency response of the generator in this range is from 1.5 kHz to 6.3 kHz. The range of the AF sound spectrum is from 1.4 kHz to 2.8 kHz. Maximum values of the energy level - f≈2.0 kHz that corresponds to the frequency of 1.6-2.4 kHz. By calculation for this range the energy characteristics of the static and dynamic components of the pulsating fluid flow were determined. This made it possible to determine that the efficiency of the cavitation generator, all other conditions of the coal-bed hydro loosening being equal, is 4.8–1.2 times higher than the efficiency of the static impact. That leads to a decrease of energy consumption by about 50%. The proposed method for evaluating the effectiveness of the device for hydro-impulsive action on a coal bed is of practical importance. It allows to evaluate the effectiveness of the operation of cavitation generators in the technological process of hydro impulsive action without additional experimental studies.

Keywords: coal bed, hydro impulsive loosening, cavitational generator, sound spectrum.

Introduction. It is known that the imposition of dynamic loads on the block-seamed structure of a coal-bed increases the speed and quality of its hydro loosening. In the Institute of Geotechnical Mechanics of the NAS of Ukraine it was developed promising device for hydro impulsive impact on the coal-bed [1]. The device is created based on the standard sealer of the well "Taurus".

The generator of cavitational self-oscillations (hereinafter the generator) is installed in the tip of the sealer. This made it possible to eliminate energy losses and transfer the dynamic load to the coal-bed directly in the filtration section of the well.

The generator is the Venturi tube of special geometry in the flow part of which high-frequency self-oscillations of fluid pressure occur [2, 3]. In the filtration section of the well, the energy of the cavitational oscillations of liquid medium is transformed into the energy of a hydro-impulse vibration. High-frequency impact of power pulses on the block-seamed structure of the coal-bed leads to its fatigue state. Therefore, even at medium stresses that do not reach the strength of coal [4], a multidirectional network of microcracks develops and it is occurred the discontinuity in the coal-bed.

The indisputable advantage of this device, in contrast to the known mechanisms and methods [5-7], is the absence of additional energy sources and moving mechanical parts. The generator is located in the well and all the energy of cavitation self-oscillations is spent on the hydro impulsive loosening of the bed. When it is conducted the mining operations at threatened and dangerous beds by sudden coal and gas emissions, the "Rules ..." [8] defines the requirements for forecasting and controlling the danger of coal-bed for gas-dynamic phenomena (GDP). In order to control the dynamic parameters and evaluate the effectiveness of the new method of hydroimpulsive loosening [9], based on standard methods [8], new methods were developed to monitor the state of the coal bed and control the hydroimpulsive effect. The developed methods make it possible to control the process of hydro-loosening, but do not allow to estimate the effectiveness of the device operation. Therefore, the purpose of this work is to determine the efficiency of the device and evaluate its effectiveness.

To achieve this goal, it was used the results of mining and experimental works, the results of bench tests of the device for hydro impulsive impact on the coal bed, theoretical studies of the energy characteristics of stationary and pulsating fluid flow.

Validation of the range for research. The basis of our research will take the results of mining and experimental works at the pressure of the fluid at the generators inlet $P_n = 11$ MPa.

In fig. 1 it is shown the amplitude-frequency (AF) spectrum of the sound of a hydro-impulsive loosening of a coal bed, recorded by the ZUA-98 equipment [10, 11].

The seismogram reflects the intensity of acoustic emission (AE) of the signal in the frequency range from zero to 3.0 kHz. The soundtrack spectrum of AE characterizes its energy at different intensity of the process. In our example, the range of low-frequency vibrations of 100-150 Hz is associated with electrical noise. Part of the energy of high-frequency oscillations of 200-800 Hz is associated with the process of fluid filtration and the development of cracks around the well, and some with ultrasonic vibrations of the coal bed.

The high-frequency region of the spectrum is associated with pressure pulses, which are realized by the device generator. If there are no high-frequency components in the AF spectrum with a high level of energy of the sound impulse of a hydro-impulse effect, then the generator operates without load, i.e. hydro impulsive loosening of bed does not occur.

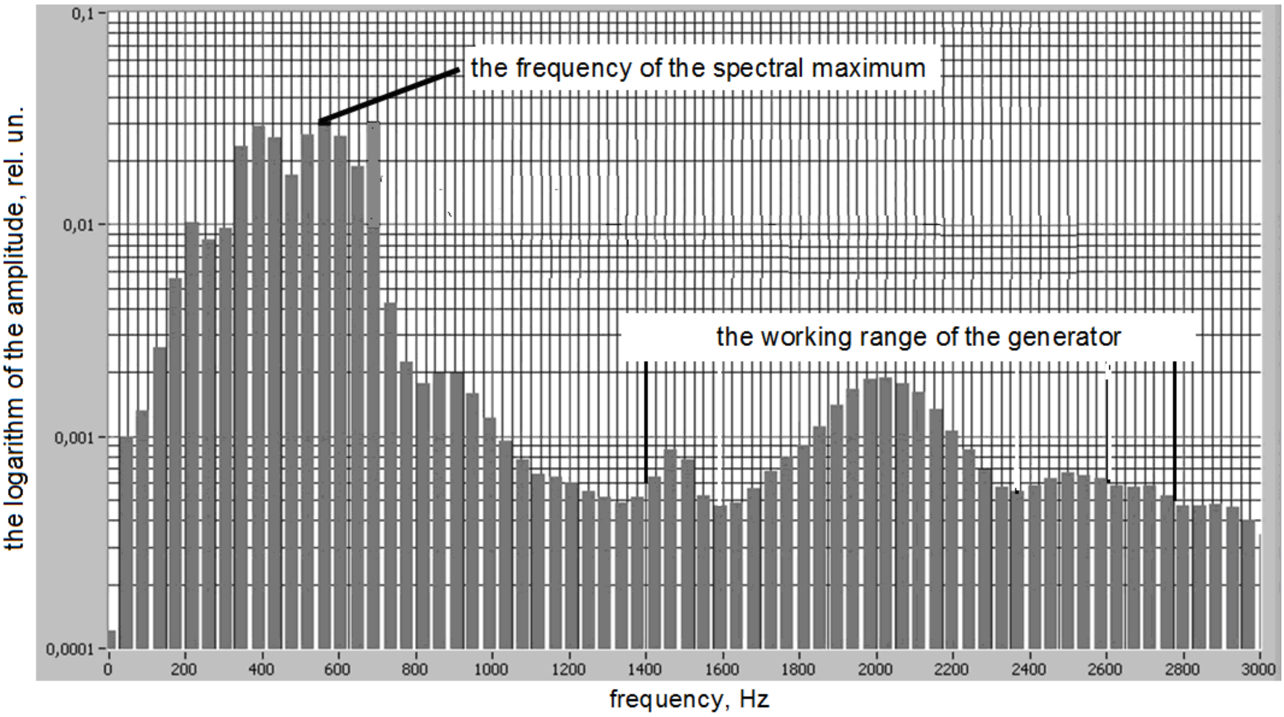

Figure 1 - Amplitude-frequency spectrum of sound accompaniment of hydro-impulsive loosening of coal bed (copy from operator’s monitor)

By the results of the control it was found that at P_n = 11 MPa, the active process of hydro impulsive loosening starts at a backup pressure in the well ≈1.5 MPa. The most intense cracking in the bed occurs at the backup pressure from 3.0 MPa to 6.0 MPa within 5-6 minutes, while its maximum was 7.5 MPa. After that, the backup pressure sharply decreased to 2.0 MPa, and then, after 20-30 seconds, to ≈ 0.8 MPa.

The analysis of the results of the monitoring of the backup pressure of the liquid in the well and the sound accompaniment spectrum of the hydro-impulsive loosening (see Fig. 1) are allowed to establish the following:

1. The active stage of hydro impulsive loosening of the bed occurs within 6-7 minutes at the backup pressure of the liquid in the well from 1.2 MPa to 7.5 MPa. The frequency response of the generator in this range is from 1.5 kHz to 6.3 kHz;

2. The range of the AF spectrum of the signal generator operation AE is from 1.4 kHz to 2.8 kHz. The most effective stage corresponds to the frequency of 1.6-2.4 kHz, and the maximum values of the energy level - f≈2.0 kHz.

The method of calculating the generator efficiency. The useful energy that realized under hydro-impulsive action consists of static and dynamic components. Following the works [12], the total energy flow $Э$ is determined by the expression

$$E = P_p Q_n + \Delta P \Delta Q\,, \tag{1}$$

where $P_pQ_n = E_S$ – it is the energy flow corresponding to a steady flow, not associated with oscillations. It is determined by the backup pressure P_p and flow rate through the pump Q_n. The second term in equation (1) is determined by the oscillatory components of pressure – ΔP and flow rate ΔQ and called the flow of vibrational energy.

Oscillatory component ΔQ is determined from the condition of the balance of its equality of the detached part of the settled cavitation cavity ΔV_c multiplied by oscillation frequency f

$$\Delta Q = \Delta V_c f. \tag{2}$$

The frequency of self-oscillations f is determined by the formula [13]

$$f = Sh_e \frac{v_{cr}}{r_{cr}} \tau, \tag{3}$$

where Sh_e – Strouhal number, whose approximation equation is determined on the basis of experimental data Sh_e=0,0066 r_{cr}+0,0749 with certainty R^2=0,99; τ, r_{cr} и v_{cr} – the cavitation parameter, the radius of the generator's critical section, and the fluid velocity were determined by known formulas.

The amplitudes of the self-oscillations of the volume $\Delta V_к$ were determined from the condition of the maximum volume of the settled cavitation cavity at the moment of its separation at $\ell_c \leq \ell_d$ (where ℓ_c and ℓ_d – axial lengths of the cavern and generator diffuser):

$$\Delta Vc = \frac{\pi \ell_c}{2}\left[3r_{cr}^2(1-\mu) + 3r_{cr}\ell_c\left(tg\frac{\beta}{2} - tg\frac{\alpha}{2}\right) + \ell_c^2\left(tg^2\frac{\beta}{2} - tg^2\frac{\alpha}{2}\right)\right], \tag{4}$$

where β – expansion angle of the generator diffuser, α – the angle of expansion of the fluid jet, μ – generator flow rate coefficient equal to 0,95.

The axial length of the cavity depending on the degree of development of cavitation is determined in accordance with [14] by the formula

$$\ell_c = \frac{r_{cr}}{tg\dfrac{\beta}{2}} \cdot \left(\sqrt{\frac{\mu}{1-\sqrt{0{,}88-\tau}}} - 1\right), \tag{5}$$

Thus, the calculation of the total energy flow E (1) is made taking into account the oscillatory components of the flow rate ΔQ according to the formula (2) taking into account (3)÷(5), and the pressure P - according to the refined linear mathematical model of the cavitation generator [15].

Calculated energy fluxes are obtained at discharge pressures P_n = 11 MPa, expansion angle of the generator diffuser β=20° and jet extensions α = 1,35°, sound velocity in fluid c = 1100 м/с, flow rate coefficient μ = 0,95 and saturated vapor pressure P_c = 0,0024 MPa.

Analysis of the results. Calculated dependencies of oscillatory components of pressure ΔP, flow rate ΔQ and frequency f from backup pressure P_n in the range of its change from 0,5 to 9 MPa are presented on fig. 2.

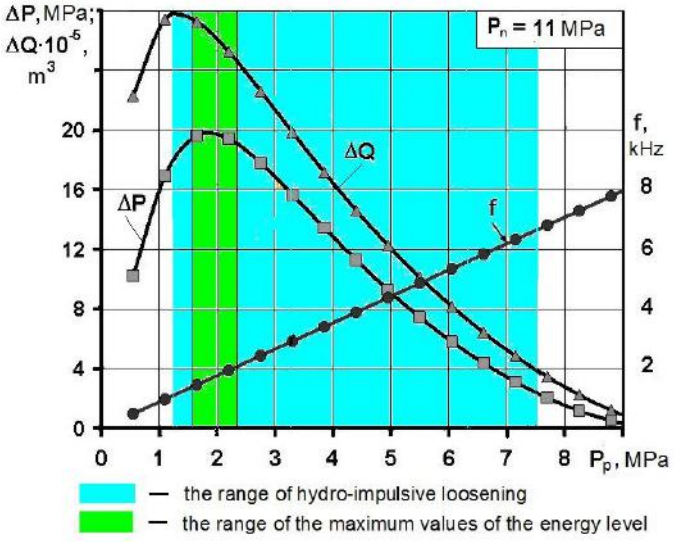

Figure 2 - Calculated dependencies of oscillatory components ΔP, ΔQ and frequency f from backup pressure of the liquid in the well P_n

The figure also shows the established range of the active stage of hydro-loosening at the pressure of the liquid in the well from 1.2 MPa to 7.5 MPa and the AF zone of the AE signal at the most effective stage of the generator operation 1.6-2.4 kHz.

From the above results it can be seen that the range of the AF spectrum of the AE signal of the most effective stage of the generator operation (1.6-2.4 kHz) corresponds to the backup pressure in the well from 1.2 to 3 MPa.

The analysis of the established dependencies $\Delta P=f(P_p)$ and $\Delta Q=f(P_p)$ shows that with growth of P_p values of oscillatory components ΔP, ΔQ increases dramatically and, at certain values of $P_p\approx1.8$ and $P_p\approx1.3$ MPa respectively, reach their maximum. The maximum value of ΔP approximately 1.9 times exceeds the pressure at the inlet to the generator $P_н$. Further, with an increase in the backup pressure of the liquid in the well, it is observed decreasing of their values to almost zero.

The calculations allowed us to determine the energy flux, which corresponds to oscillatory components $E_o=\Delta P\cdot\Delta Q$, and the total energy flux E (Fig. 3).

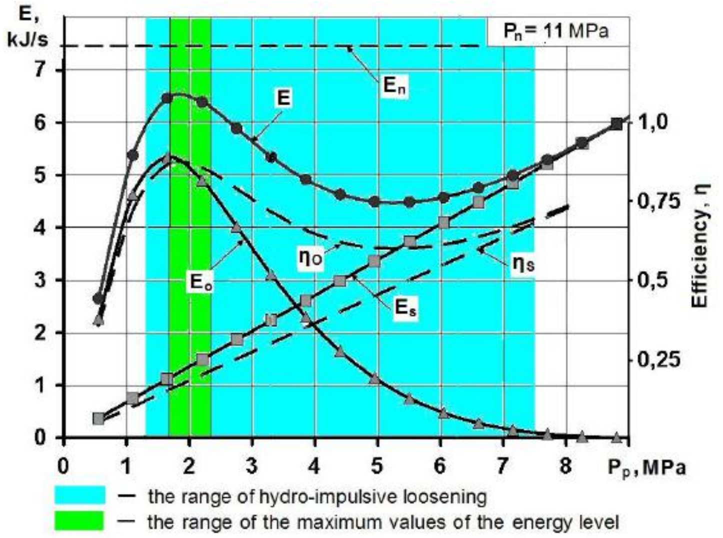

Figure 3 – Calculated dependences of energy fluxes and efficiency on the backup pressure P_p

From the established dependencies it is follows:

1. Relation $E_s=f\,(P_\text{p})$ under the steady flow of liquid, is linear. Values E_s with the increasing of backup pressure increase and tend to the maximum value that is developed by the pump $E_\text{п}$.

2. Under hydro impulsive action, when the backup pressure P_p varies from 0 to ≈1.5 MPa, the dynamic component E_o of the energy flux increases from zero to the maximum value $E_o \approx 5.4$ kJ / s. Further, with increasing of the backup pressure, the value of the dynamic component E_o monotonously decreases, reaching zero at $P_p \approx 8.5$ MPa. This is due to decreasing in the level of pressure fluctuations ΔP and volume flow rate ΔQ under increasing the backup pressure P_p;

3. With an increasing of the backup pressure value $P_\text{п}$ from zero to ≈1.7 MPa, the total energy flux E increases under hydrodynamic action, reaching a maximum value of $E_\text{max}\approx$ 6.5 kJ / s, with its subsequent decreasing. When $P_\text{p} \approx 5.5$ MPa, the total flux E reaches the minimum value ≈ 4.5 kJ / s. A further increasing of the value of E is explained by an increase in the component of the energy flux corresponding to the steady-state flow E_o, under a significant decreasing of the level of dynamic effects on the liquid.

The analysis of the obtained results allows to estimate the efficiency of hydro loosening under the pulsed or static injection of fluid into the coal bed.

The expression for efficiency under impulse action is represented as

$$\eta_o = \frac{E}{E_n}, \tag{6}$$

and under the static injection –

$$\eta_s = \frac{E_s}{E_n}\,. \tag{7}$$

Consideration of the calculated dependencies of efficiency under pulsed and static effects on the bed on the backup pressure P_p (see Fig. 3) shows that with increasing of backup pressure P_p from 0.5 MPa the efficiency $\eta_\text{им}$ first increases sharply, reaching a maximum value of 0.87 at $P_\text{p} \approx 1.9$ MPa, and, further, decreases to 0.6 at $P_\text{p} \approx 5.5$ MPa.

This behavior of $\eta_\text{o}=f\,(P_\text{p})$ is caused by the nature of the dependence of E on P_p (Fig. 3). A further increasing of efficiency η_o at $P_\text{p} > 5.5$ MPa is explained by the significant domination of the energy flux corresponding to the steady-state flow over the oscillatory component, which practically acquires a zero value at $P_\text{p} \approx 8.5$ MPa.

Comparison of dependencies $\eta_\text{o}=f\,(P_\text{p})$ and $\eta_\text{ст}= f(P_\text{p})$ shows that in the range of backup pressure P_p variation from 0.5 MPa to 6 MPa, the impulse effect on the coal bed is much more effective than the static injection.

Conclusions. Analysis of the results of mining and experimental studies made it possible to establish the working frequencies range of the device for the hydro impulsive effect on the coal bed. By calculation for the established frequency range the energy fluxes are determined corresponding to the static and hydro impulsive injection of the liquid into the coal bed. It made it possible to establish that:

– ceteris paribus (in pressure of injection and in the range of backup pressure from 1 to 6 MPa) the efficiency of hydro impulsive action exceeds the efficiency of static action by about 4.8÷1.2 times, which leads to decreasing in energy consumption by about 50%;

–the proposed method for evaluating the effectiveness of the device for hydro-impulsive action on a coal bed is of practical importance. At the design stage of new or improved existing equipment it allows to evaluate the effectiveness of the operation of cavitation generators in the process of hydro impulsive action without additional experimental studies.

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Анотація. В роботі приведені результати гірничо-експериментальних робот, стендових випробувань і теоретичних досліджень енергетичних характеристик статичного та імпульсного потоків рідини, які дозволяють оцінити ефективність роботи кавітаційного генератора при гідроімпульсному розпушуванні викидонебезпечних вугільних пластів. Генератор є трубкою Вентурі спеціальної геометрії, в проточній частині якого виникають високочастотні автоколивання тиску рідини. Перевагою даного пристрою є відсутність додаткових джерел енергії і рухомих механічних частин. Генератор розташовується у фільтраційній частині свердловини, тому вся енергія кавітаційних автоколивань витрачається на гідророзпушування пласта. За амплітудно-частотного (АЧ) спектру звукового супроводу гідроімпульсної дії і тиску підпору рідини в свердловині встановлена активна стадія гідроімпульсного розпушування і ефективний діапазон АЧ спектру акустичного сигналу роботи генератора. Активна стадія розпушування пласта відбувається протягом 6-7 хвилин при тиску підпору рідини в свердловині від 1,2 МПа до 7,5 МПа. Частотна характеристика генератора у даному діапазоні складає від 1,5 кГц до 6,3 кГц. Діапазон АЧ звукового спектру складає від 1,4 кГц до 2,8 кГц. Максимальні значення рівня енергії – $f \approx 2{,}0$ кГц відповідають частоті 1,6-2,4 кГц. Розрахунковим шляхом для цього діапазону визначені енергетичні характеристики статичної та динамічної складових пульсуючого потоку рідини. Це дозволило визначити, що ККД кавітаційного генератора, за інших рівних умов гідророзпушування вугільного пласта, у 4,8…1,2 рази перевищує ККД статичної дії. Це призводить до зниження питомих енерговитрат приблизно на 50 %. Запропонований спосіб оцінки ефективності роботи пристрою для гідроімпульсної дії на вугільний пласт має важливе практичне значення. Він дозволяє оцінити ефективність роботи кавітаційних генераторів в технологічному процесі гідроімпульсної дії без додаткових експериментальних досліджень.

Ключові слова: вугільний пласт, гідророзпушування, кавітаційний генератор, звуковий спектр.

Аннотация. В работе приведены результаты горно-экспериментальных работ, стендовых испытаний и теоретических исследований энергетических характеристик статического и импульсного режимов потока жидкости, которые позволяют оценить эффективность работы кавитационного генератора при гидроимпульсном рыхлении выбросоопасного угольного пласта. Генератор представляет собой трубку Вентури специальной геометрии, в проточной части которого возникают высокочастотные автоколебания давления жидкости. Преимуществом данного устройства является отсутствие дополнительных источников энергии и подвижных механических частей. Генератор располагается в фильтрационной части скважины, поэтому вся энергия кавитационных автоколебаний расходуется на гидрорыхление пласта. По амплитудно-частотному (АЧ) спектру звукового сопровождения гидроимпульсного воздействия и давлению подпора жидкости в скважине установлена активная стадия гидроимпульсного рыхление и эффективный диапазон АЧ спектра акустического сигнала работы генератора. Активная стадия рыхления пласта происходит в течении 6-7 минут при давлении подпора жидкости в скважине от 1,2 МПа до 7,5 МПа. Частотная характеристика генератора в данном диапазоне составляет от 1,5 кГц до 6,3 кГц. Диапазон АЧ звукового спектра составляет от 1,4 кГц до 2,8 кГц. Максимальные значения уровня энергии – $f \approx 2{,}0$ кГц соответствует частоте 1,6-2,4 кГц. Расчетным путем для этого диапазона определены энергетические характеристики статической и динамической составляющих пульсирующего потока жидкости. Это позволило определить, что КПД кавитационного генератора, при прочих равных условиях гидрорыхления угольного пласта, в 4,8…1,2 раза превышает КПД статического воздействия. Это приводит к снижению удельных энергозатрат примерно на 50 %. Предложенный способ оценки эффективности работы устройства для гидроимпульсного воздействия на угольный пласт имеет важное практическое значение. Он позволяет оценить эффективность работы кавитационных генераторов в технологическом процессе гидроимпульсного воздействия без дополнительных экспериментальных исследований.

Ключевые слова: угольный пласт, гидрорыхление, кавитационный генератор, звуковой спектр.

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