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CONTROL OF WAVE PROCESSES IN THE ROCK ENVIRONMENT TO REDUCE THE RISK OF GAS DYNAMIC PHENOMENA

[1]Makeiev S.Yu., [1]Kurnosov S.A., [1]Ryzhov H.O., [2]Nazieh H.

[1]Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine, [2]Zarqa University

Abstract. The article is aimed at developing new methods for controlling wave processes in a rock massif during the driving of development workings and coal mining in stopes. When carrying out underground mining, accidents are often caused by the fact that the safety regulations are not always strictly followed due to the difficulty in determining the causes and mechanisms for the initiation of gas-dynamic phenomena. The aim of the study was to create an adequate model of the process of generation of fracture wave foci in a coal-rock massif and to identify ways to create new method to control this phenomenon. Research tasks: to perform a theoretical analysis of the self-oscillatory nature of the formation of a self-sustaining destruction wave during the process of coal and gas outburst; to create a model adequate to this process; to identify ways to eliminate the potential possibility of the emergence of gas-dynamic phenomena.

The mechanism of gas-dynamic phenomena through the use of concept of the flow of emissions in the form of a thermal explosion was reviewed, which allows to present the phenomenon of coal and gas emission as a result of the autowave process of self-sustaining propagation of a wave with the oscillator and spin instability. A mathematical model is proposed which describes the propagation of fracture wave in coal as a result of reaching a critical pressure gradient of the desorbed gas. The scientific significance of the research lies in the fact that an analytical expression was obtained to determine velocity of the compression wave propagation in the layer depending on the critical stress gradient. According to this expression, there are two different modes of the wave destruction process, which differ by propagation speed, structure and properties of the wave. This necessitates the use of a controlled physical-chemical impact (FCI), as it is less dynamic. A dimensionless empirical coefficient is proposed to assess the efficiency of the FCI and the degree of change in the state of the coal layer at the micro- and macrolevels. Its use will make it possible to select such a type of FCI, which will change the critical stress gradient in the coal to safe values. This will prevent the generation and development of a fracture wave characterized by a critical propagation velocity, and, thereby, will reduce the risk of gas-dynamic phenomenon occurrence.

The results of the research can be used in the development of scientific prerequisites for improving the methods and means of controlling the stress-strain state and gas dynamics of a coal-rock massif by using various working environments.

Keywords: gas-dynamic phenomenon, fracture wave, pressure distribution, stress gradient, physical-chemical impact.

Introduction. When conducting mining operations have to deal with such dangerous gas-dynamic manifestations as the outbursts of coal, rocks and gas, which often lead to death of people and loss of expensive equipment. Currently, a lot of experience of dealing with these negative underground phenomena accumulated, but this problem has not been solved [1]. Perhaps, this is due to the fact that while there is no single evolutionary structural model for gas-dynamic phenomena, which would determine the causes and mechanism of their origin. But, the choice of effective means for controlled stimulation of coal massif is impossible without a detailed consideration of the most realistic models of the disturbing processes.

One of the latest and the most accurate models, in our opinion, is the cluster-synergetic concept of the flow of outbursts in the form of thermal explosion [2, 3]. The model describes the gradual process of evolution of the zone sudden emission (outburst): fusion of concentrated micro-cracks and changes in the structure of substance and further abnormal abnormal generation of methane from propagating cracks with a sharp nonlinear rise in temperature and the increase of dissipation energy that makes a metastable system moving and unstable. This sequence allows to consider the phenomenon of coal and gas outburst as well with the participation of autowave propagation process of a self-sustaining wave with the oscillator and spin instability. This interpretation expands the range of search of control actions to create new effective ways to control gas-dynamic phenomena.

The aim of the study was to create an adequate model of the process of generation of fracture wave foci in a coal-rock massif and to identify ways to create new ways to control this phenomenon.

The objective of the research is based on theoretical analysis of self-oscillating character of the propagation of a self-sustaining wave of destruction in the process of coal and gas outburst; to create an adequate for this process model and to identify ways to address the potential origin of the gas-dynamic phenomena.

Methods. A wave of coal and gas outburst is a typical example of a traveling front. The autowave combustion processes are the closest in ideological terms and in terms of the mathematical apparatus similar to the problem of outbursts, which directly lead to a heat explosion. The combustion process is described by the differential equations of the form similar to the terms of mass transfer phenomena of diffusion and filtration.

The well-known models [4, 5] associated with the pulsation velocity of traveling front, a typical example of which is the wave of coal and gas outburst. The self-oscillating combustion and spin waves overlap with them by the same principle.

Traveling front with self-excited oscillations in the combustion process is described by the equations of heat conduction with nonlinear source J.

The investigation of traveling front motion at change of $Le = \zeta/D$ (Le – Lewis number, $\zeta = \chi/\rho c_p$ – coefficient of thermal diffusivity, m^2/s; χ – thermal conductivity coefficient, W/(m·K); ρ – the density of environment, kg/m^3; D – the diffusion coefficient, m^2/s) and temperature in the unperturbed environment (T_0) showed that vibrational instability of this front is observed at certain ratios.

If source function of self-oscillating combustion is equal to:

$$J = \frac{nx_0}{c_p exp\left(\frac{E}{RT}\right)}, \tag{1}$$

where J – the source function, mole·K/m^3; n – the concentration of the reagent that simulates combustion reaction, mole/m^3; x_0 – pre-exponential factor, J/kg; c_p – specific heat of the environment at constant pressure, J/(kg·K); E – the activation energy, J/mole; R – the gas constant, J/(mole·K); T – the absolute temperature, K,
then the value is

$$T_0 = \frac{R}{E} Le\left(T + \frac{\gamma}{c_p}\right)^2 . \tag{2}$$

where γ – specific energy perturbation, J/kg.

So, when the main mass transfer occurs due to the diffusion and when T_0 is greater than critical temperature, the instability manifests in the form of pulsation of the instantaneous speed of the traveling front relatively stationary values.

The similar pattern occurs in the processes of coal and gas outburst. In a two-dimensional environment, there is also the instability of a flat front propagation, which is called spin combustion. It consists on the fact that there is a similar zone of localized temperature mentioned in [2, 3], which moves along the combustion front. Propagation of the entire front leads to the gradual evolution of the zone of sudden outburst and directly to thermal explosion through the autowave processes.

The identity of the above phenomena within a single mathematical model is shown in [6].

Let’s analyze the processes of coal and gas outbursts occurrence and running considering their autowave character.

Under the conditions of outburst generation, the destruction of the environment in case of layer-by-layer separation occurs when reaching a certain critical gas pressure gradient $\left(\frac{dP}{dx}\right)_{cr}$, which causes tensile stresses in the coal equal to its ultimate strength [7].

Based on this, by analogy with the classical theory of combustion [4, 5], the propagation of the destruction wave will be determined by the following equation:

$$K\frac{d^2P}{dx^2} - fv_w\frac{dP}{dx} + v_g = 0, \tag{3}$$

where P – the gas pressure, Pa; K – the specific mass transfer coefficient, m^3·s; f – the capacitive parameter, m·s^2; v_w – the speed of propagation of the wave of destruction, m/s; x – the spatial coordinate associated with the wave, m; v_g – the specific speed of gas saturation per unit area, kg/(s·m^2).

The specific speed of the gas saturating v_g is different from zero only in the zone of formation of cracks, the width of which is constant.

The task is to find a solution of the equation (3) satisfying the boundary conditions in the linear region (Fig. 1)

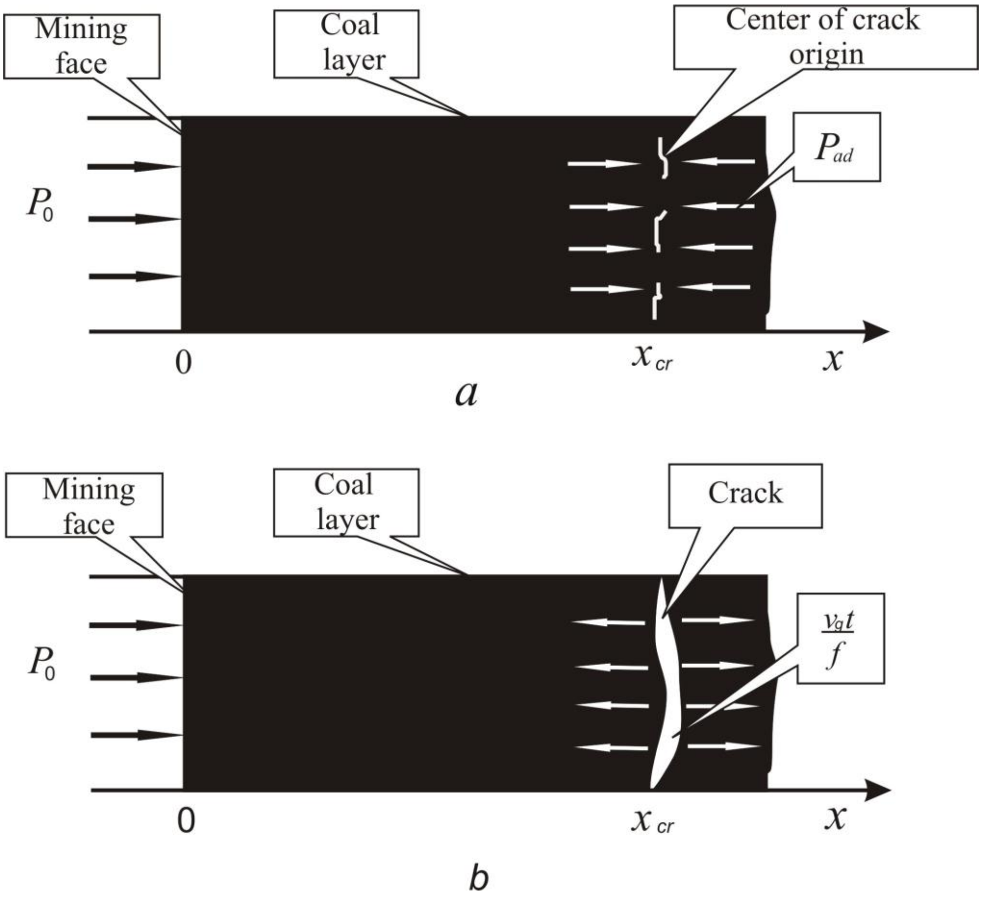
$$P|_{x=0} = P_0; \qquad P|_{x=\infty} = P_0 + \frac{v_g t}{f} = P_{ad}, \tag{4}$$

where P_0 – the atmospheric pressure, Pa; P_{ad} – pressure of adsorbed gas, Pa; t – a limited time during which gas is released and rapidly desorbed when destruction surface is formed, s.

As a result of solving equation (4) we obtain the pressure distribution in the fracture zone:

$$\frac{P-P_0}{P_{ad}-P_0}=\psi+\frac{1-exp\left[-u^2(1-\psi)\right]}{u^2}, \tag{5}$$

where $\psi=\dfrac{x}{v_w t}$ – the dimensionless width of the fracture zone, $u=v_w\sqrt{\dfrac{f}{K\cdot t}}$ – the dimensionless velocity of wave propagation.



a - the origin of the destruction center, b - opening of the crack as a result of desorption

Figure 1 – Scheme of the calculation area

As a result of the formation of a crack and the release of desorbed gas into it, a compression wave propagates through the coal layer.

According to equation (5), at the beginning of the outburst process (at x = 0) the value of the dimensionless relative pressure will be:

$$\frac{P-P_0}{P_{ad}-P_0}=\frac{1-exp\left(-u^2\right)}{u^2}. \tag{6}$$

To find the speed of the wave effects we obtain the equation (Fig. 2)

$$\sigma_{cr} = \frac{1-exp\left(-u^2\right)}{u}. \tag{7}$$

Here $\sigma_{cr} = \sqrt{\frac{K \cdot t^3}{f}} \frac{\left(\frac{dP}{dx}\right)_{cr}}{P_{ad} - P_0}$ is a dimensionless value of the critical stress gradient.

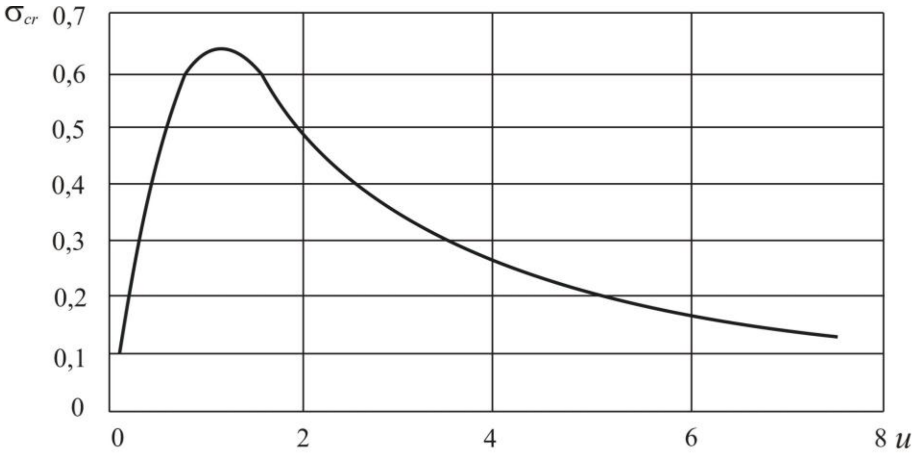


Figure 2 – Dependence of the value of the critical dimensionless gradient σ_{cr} on the dimensionless speed of wave propagation *u*

As it can be seen from Fig. 2, the solution of equation (6) exists at $\sigma_{cr} < 0{,}64$ and it is not the only one. Two values of *u* correspond to one and the same value of σ_{cr}. Accordingly, there are two different stationary modes of the wave fracture process, which differ by the speed of propagation, structure and properties of the wave. And in the vicinity of $u \approx 1.0$ there is a zone of oscillatory instability.

By substituting in (7) the value of σ_{cr}, we obtain $\sqrt{\frac{Kt}{f}} \frac{\left(\frac{dP}{dx}\right)_{cr}}{P_{ad} - P_0} = \frac{1-exp\left(-u^2\right)}{u}$,

where $u = v_w \sqrt{\frac{t \cdot f}{K}}$.

At $u \ll 1$, the expression $\frac{1-exp\left(-u^2\right)}{u}$ tends to *u*, then, by performing the transformation, it is easy to obtain a formula for a "slow" wave. The "slow" wave of destruction (growing branch on the graph at $u \ll 1$) has a speed

$$v_w = \frac{K}{f} \frac{\left(\frac{dP}{dx}\right)_{cr}}{P_{ad} - P_0}. \tag{8}$$

At $u >> 1$, the expression $\exp(-u^2)$ tends to zero, then, performing the transformation, is easy to obtain the formula for a "fast" wave. The "fast" wave (falling branch on the graph at u >>1) ceases to depend on the mass of coal outburst

$$v = \frac{P_{ad} - P_0}{t\left(\frac{dP}{dx}\right)_{cr}} . \quad (9)$$

As can be seen from Figure 2, the velocities of these two waves differ by about ten times.

Results and discussion. The existence of heterogeneities in a coal layer, leading to the appearance of several variables $\left(\frac{dP}{dx}\right)_{cr}$, and thus two solutions of equation (3), create the necessary prerequisites for the unstable flow of the process: for example, oscillations arising in one of the directions. These circumstances help to explain both the oscillatory character of the outburst wave, and its cyclical nature observed sometimes: the alternation of intensely flowing process with seemingly stops (stage of "slow" wave).

This is consistent with the fact that the primary destruction has two phases: initial and final [8]. The initial stage corresponds to a variable from slow to accelerated crack growth and is characterized by smooth mirror morphology of the fracture surface. With further growth of the rupture area at the final stage of rapid destruction, a rough surface is formed. Thus, the relationship between the energies of generation and micro-branching of the crack is manifested, which determines the morphology of the destruction process. This suggests that the outburst stops at the stage of slow crack growth, which is associated with a slow wave of the material fracture front.

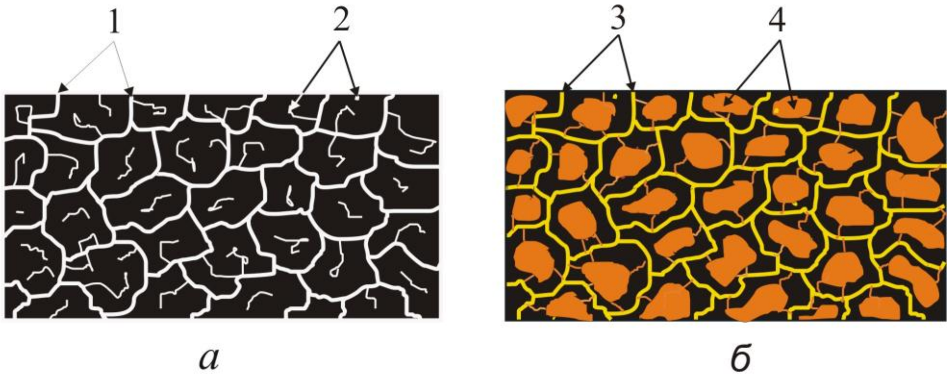
If two types of fracture waves are involved in the generation of gas-dynamic phenomena: "slow" and "fast", then the impact on the coal environment should be less dynamic, which is typical of methods based on substances that change the phase state.

This method of impact for areas with abrupt changes in stress and abnormally variable homogeneity and permeability of coal and rocks can be attributed to the physical-chemical impact (FCI) on the massif [9]. Compositions capable of first making interstructural plasticization of the carbonaceous medium followed by hardening at the macro level are used as the working fluid. This allows to change to a safe limit the relative deformations in the hazardous layer, as well as increase the homogeneity of the structure of the massif [10, 11] (Fig. 3). This prevents the branching of cracks, transfers consumption of energy supplied from the process of brittle fracture to the process of plastic deformation, increases the impact strength, and, thus, helps to suspend the process of origin and development of the gas-dynamic phenomenon.

Based on the foregoing, an empirical factor in (6) is added, defining the influence of PCI on change in the characteristics of the kinetic strength of coal, comprehensively taking into account the basic factors of stimulation: concentration of reagents in the injection composition, time and pressure of injection, the time change of the phase state of the solution and degree of filling by it fractured-porous structure of coal. Finally, we get

$$\sigma_{cr} = h_w \frac{1-exp\left(-u^2\right)}{u}, \tag{10}$$

where h_w – an empirical dimensionless coefficient that takes into account the effect of physical-chemical impact, and when при $h_w > 1$ occurs hardening of the massif in the macro-level and when $h_w < 1$ – plasticization and disintegration at the micro-level.



1 - macrocracks, 2 - microcracks, 3 - areas of inter-block hardening, 4 - areas of interstructural plasticization; a – before physical-chemical impact, b – after physical-chemical impact

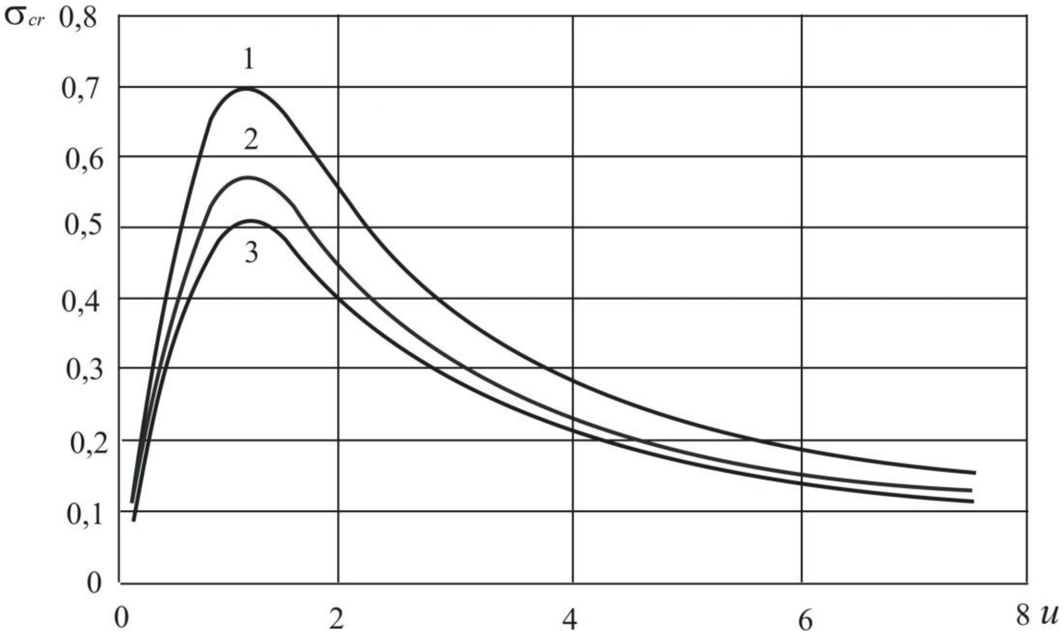
Figure 3 – The degree of the structure homogeneity of coal-rock massif

The putting of empirical dimensionless factor h_w, allows using the critical gradient σ_{cr} to evaluate the effectiveness of PCI and the degree of state change of coal layer when gas-dynamic process is originated.

Based on [12, 13], examples of graphical dependences of σ_{cr} from u for different coefficients of physical-chemical action h_w are obtained, which are presented in Figure 4.

In accordance with the experimentally [12, 13] obtained ranges of variation in key parameters of influence on the rock massif it is established that the hardening leads to an increase of the maximum value of the stress gradient σ_{cr} with increasing u. In particular, the FCI using a strengthening solution with a concentration 15-25 % corresponds to the change of the coefficient h_w in the range of 1.05 to 1.20. The use of plasticizing or disintegrating solution as a working fluid for stimulation corresponds to a decrease in the maximum value of the gradient σ_{cr}. Thus, the use of lignosulfonate with a concentration of 5-40% is identical to the range of the coefficient h_w from 0.98 to 0.70. And the use of disintegrating solution with a concentration of 10-20% corresponds to a change of the coefficient h_w from 0.90 to

0.80, which significantly reduces the probability of risk of gas-dynamic phenomenon occurrence.



1 – h_w = 1,1; 2 – h_w = 0,9; 3 – h_w = 0,8

Figure 4 – Dependence of the dimensionless critical gradient σ_{cr} from the dimensionless speed of wave propagation u at different coefficients h_w

Conclusions. The processes of gas-dynamic phenomenon origination and flowing with taking into account their autowave character are analyzed. By analogy with the classical theory of combustion, a mathematical model is proposed that describes the propagation of the fracture wave in coal as a result of achieving a critical pressure gradient of the desorbed gas. This causes tensile stresses in coal equal to the limits of its strength.

The pressure distribution in the vicinity of the center of origin of the fracture wave is established. An expression is obtained to determine the velocity of propagation of the compression wave u in the layer depending on the critical stress gradient σ_{cr}. According to this dependence, the same value of σ_{cr} corresponds to two values of u. That is, there are two different stationary modes of the wave process of destruction, which differ by the speed of propagation, structure and properties of the wave. These circumstances allow us to explain the oscillatory nature of the wave of destruction and its cyclical nature - the alternation of an intensive process (stage of "fast" wave) with stops (stage of "slow" wave).

The presence of two types of fracture waves necessitates applying of coal environment stimulation by the substances capable to change their phase state; this is one of the ways to eliminate a potential possibility for and reduce the risk of gas-dynamic phenomena occurrence [14].

A dimensionless empirical coefficient h_w is proposed to measure the effectiveness of FCI and the degree of change in the state of the layer at the micro and macro levels. The application of the coefficient h_w allows to choose such type of FCI that changes the critical gradient σ_{cr} to safe values which characterize the state of the rock massif at the time of the gas-dynamic phenomenon origin. This prevents development of waves of destruction, characterized by a critical rate of propagation u.

The results of the research can be used in the development of scientific prerequisites for improving the methods and means of controlling the stress-strain state and gas dynamics of the coal massif using different working environments.

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About authors

Makeiev Serhii Yuriiovych, Candidate of Technical Sciences (Ph.D.), Senior Researcher, Senior Researcher in Department of Problems of Mineral Mining at Great Depths, Institute of Geotechnical Mechanics named by N. Poljakov of NAS of Ukraine (IGTM NAS of Ukraine), Dnipro, Ukraine, smakeev@ukr.net

Kurnosov Serhii Anatoliiovych, Doctor of Technical Sciences (Sci.D.), Senior Researcher, Senior Researcher in Department of Problems of Mineral Mining at Great Depths, Institute of Geotechnical Mechanics named by N. Poljakov of NAS of Ukraine (IGTM NAS of Ukraine), Dnipro, Ukraine, sakurnosov@gmail.com

Ryzhov Hennadii Oleksandrovych, Junior Researcher in Department of Problems of Mineral Mining at Great Depths, Institute of Geotechnical Mechanics named by N. Poljakov of NAS of Ukraine (IGTM NAS of Ukraine), Dnipro, Ukraine, rga66@ukr.net

Nazieh Hasan, Candidate of Technical Sciences (Ph.D.), Assistant Professor, Faculty of Engineering Technology, Zarqa University, Az Zarqa, Jordan, nhasan@zu.edu.jo

УПРАВЛІННЯ ХВИЛЬОВИМИ ПРОЦЕСАМИ В ГІРСЬКОМУ СЕРЕДОВИЩІ ДЛЯ ЗНИЖЕННЯ РИЗИКУ ВИНИКНЕННЯ ГАЗОДИНАМІЧНИХ ЯВИЩ

Макеєв С.Ю., Курносов С.А., Рижов Г.О., Назіх Х.

Анотація. Стаття спрямована на розробку нових методів управління хвильовими процесами в масиві гірських порід при проведенні підготовчих виробок та видобутку вугілля в очисних вибоях. Під час проведення підземних гірничих робіт часто причиною аварій є те, що не завжди точно виконується регламент робіт із забезпечення безпеки через складність визначення причин та механізмів зародження газодинамічних явищ. Метою дослідження було створення адекватної моделі процесу зародження осередків хвиль руйнування у вуглепородному масиві та виявлення шляхів розробки нових способів боротьби з цим явищем. Завдання досліджень: проведення теоретичного аналізу автоколивального характеру формування хвилі руйнування, що самопідтримується, при процесі викиду вугілля і газу; створення адекватної цьому процесу моделі; виявлення шляхів усунення потенційної можливості зародження газодинамічних явищ.

Розглянуто механізм зародження осередків газодинамічного явища на основі використання концепції перебігу викиду вугілля і газу як результату автоколивального процесу поширення хвилі, що самопідтримується, з осциляторною та спіновою нестійкістю. Запропоновано математичну модель, що описує поширення хвилі руйнування у вугіллі як результат досягнення критичного градієнта тиску газу, що десорбується. Наукове значення досліджень полягає в тому, що отримано аналітичний вираз визначення швидкості поширення хвилі стиснення у пласті залежно від критичного градієнта напруг. Відповідно до цього виразу існують два різні режими хвильового процесу руйнування, які відрізняються швидкістю поширення, структурою та властивостями хвилі. Це зумовлює необхідність застосування фізико-хімічного впливу (ФХВ), що управляє, як менш динамічного. Для оцінки ефективності ФХВ та ступеня зміни стану вугільного пласта на мікро- та макрорівні запропоновано безрозмірний емпіричний коефіцієнт. Його використання дозволить підібрати такий вид ФХВ, який змінить критичний градієнт напруги у вугіллі до безпечних величин. Це не дасть можливості зароджуватися і розвиватися хвилі руйнування, що характеризується критичною швидкістю розповсюдження, і тим самим зменшить ймовірність ризику виникнення газодинамічного явища.

Результати досліджень можуть бути використані при розробці наукових передумов до удосконалення методів та засобів управління напружено-деформованим станом та газодинамікою вуглепородного масиву з використанням різних робочих середовищ.

Ключові слова: газодинамічне явище, хвиля руйнування, розподіл тиску, градієнт напружень, фізико-хімічна дія.

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