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# FACTORS INITIATING CRACK FORMATION DURING HYDRO-IMPULSE LOOSENING OF OUTBURST-HAZARDOUS COAL SEAMS

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**Abstract.** The article is dedicated to the exploitation of outburst-hazardous coal seams at significant depths. It is known that with the increase in mining depth in the gas-saturated coal-bearing massif, changes in its stress-strain state lead to specific manifestations of outburst-hazardous coal, such as spontaneous collapse, alteration of the aggregate state and structure of hydrocarbon compounds, changes in filtration properties, and so on. These features occur when compressive deformations are replaced by tensile (shear) deformations. There is a list of methods for impacting the massif to prevent the occurrence of gas dynamic phenomena. The main task of these methods is to create additional cracks throughout the thickness of the coal seam for effective gas filtration. Along with this, during mining operations, man-made factors arise. They create additional load and change the structure and properties of outburst-hazardous coal.

The article deals with the factors of man-made impact on the heading part of the coal seam, which led to a decrease in the effectiveness of methods of preventing gas dynamic phenomena. The parameters of the processes that initiate the development of cracks around the filtration part of the well in the impulse mode of liquid injection, in the redistribution of stresses in the massif, and the case of self-destruction of coal in the heading part of the seam are considered. The theory of strength of materials is considered to establish their limit state and destruction. The paper presents the results of theoretical and experimental studies of the hydro-impulse loosening method for outburst-hazardous coal seams. The changes in deformation velocity were investigated under impulsive loading of coal relative to the modulus of elasticity in the range of $3\cdot10^2$ MPa ≤ $E$ ≤ $5\cdot10^2$ MPa. It was established that all values of impulses of self-oscillations of liquid pressure are above the curve of the limit rate of development of deformations $\dot{\varepsilon} = 10$ $s^{-1}$ at the value of the modulus of elasticity of coal $E \geq 3\cdot10^2$ MPa. We concluded that during hydro-impulse impact modes with an injection pressure of more than 5 MPa, pressure pulses of $\Delta P \geq 3$ MPa with a frequency of $f \geq 0.8$ kHz are created in the filtering part of the well. This leads to the development of shear deformations and initiates the cracks formation throughout the thickness of the coal seam.

Research on hydro-impulse impact was conducted in the mines of the Donetsk Coal Basin. The Donbas region is characterized by the most complex mining-geological conditions, especially when working with outburst-hazardous coal seams.

**Keywords:** gas dynamic phenomena, hydro-impulse loosening, crack formation, coal-gas system.

## 1. Introduction

In developed coal deposits, including the Donetsk Coal Basin, as mining depth increases and the stress-strain state of the coal-bearing massif changes, manifestations of outburst-hazardous coal peculiarities can be frequently observed. With the increase in mining depth in the gas-saturated coal-bearing massif, changes in its stress-strain state lead to specific manifestations of outburst-hazardous coal. This leads to the emergence of new natural phenomena that were not previously considered or studied at shallow depths, such as the alteration of the molecular structure of coal substance in the coal-gas system [1–3], changes in the aggregate state of methane [4], the phenomenon of methane generation [5].

Fundamental scientific research on the interaction of the coal-gas system was developed back in the 50s of the last century. Based on them, several methods of preventing gas-dynamic phenomena (GDP) and methods of controlling the effectiveness of these methods were developed [6].

Among the local methods, the methods based on the principle of liquid injection into the coal seam turned out to be the most effective. This technological process has its characteristics. The filtration characteristics of the coal seam significantly affect the injection pressure and the rate of liquid penetration into the massif. When the pressure exceeds the strength properties of the coal, cracks form in the seam due to hydraulic fracturing, leading to the development of high-pressure fluid flow.

In industrial conditions, it is impossible to control the processes of crack formation, filtration and flow of liquid in the cracked and porous structure of coal. When degassing a coal-bearing massif through wells, this factor can be neglected. During hydraulic fracturing of hazardous seams, liquid breakthrough leads to the ineffectiveness of measures to prevent GDP. In the case of a breakage face, the situation can be corrected by applying the method of hydropressing the seam. During development drift, the use of the hydropressing method is associated with a decrease in efficiency and an increase in costs. Therefore, in dangerous areas, mining is carried out with the use of blasting in the mode of shock blasting. This leads to a decrease in the speed of conducting operations by more than twice and sometimes does not exceed 1 meter per day.

Until now, the task of safely conducting operations in unprotected outburst-hazardous coal seams has not been resolved. With an increase in the depth of coal mining, a change in mining and geological conditions, and the intensification of technological processes, the parameters of liquid injection have not been changed [7].

The complexity of theoretical and experimental studies of the spontaneous destruction of a coal seam in its heading part at the GDP lies in the multifactorial nature of the stress-deformed state (SDS) of the massif. In the geological stratum, while natural transformations coal seams changed their structure and morphological properties, acquired gas saturation and emission hazard. Therefore, in conditions of great depths, they are already in a stressed-deformed state and are considered as a coal-gas system [1–3]. The condition of this system is additionally influenced by various man-made factors that arise in the massif during mining operations and the implementation of preventive measures (Fig. 1).

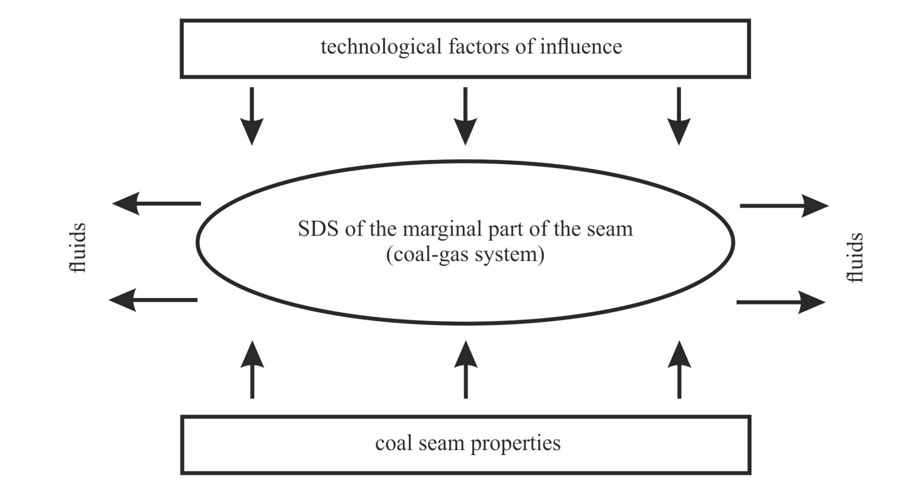



Figure 1 – Factors influencing the SDS of a coal seam in its near-cut part

Disturbance of the balance of natural forces under the influence of man-made factors leads to various forms of manifestation of GDP. Therefore, solving the problem of the gas dynamic factor has become more relevant precisely with the increase in the depth of mining operations.

Over the past few decades, a large amount of research has been carried out with the aim of establishing the most effective measures to solve the problem of GDP in coal mines of Ukraine [2–10].

The most significant contribution to the development of measures to combat GDP has been made through the application of hydraulic methods with impulse liquid injection modes [9, 10]. There are some research works in this direction worldwide [11, 12], but their effectiveness, compared to those mentioned [9, 10], is very low. For example, as a result of applying the impulse hydraulic fracturing technology, the volume of gas outburst from the well increases by 3.32 times [11]. At the same time, with the use of hydro-impulse impact, gas outburst from the well increases by 7–10 times [9], and with hydrodynamic impact, it increases by 40–100 times [10]. Research on the change in the stress-strain state of the rock mass under hydro-impulse impact was conducted in the mines of the Donetsk Coal Basin. The Donbas region is characterized by unique and complex mining-geological conditions, especially during the extraction of outburst-hazardous coal seams. Therefore, the mentioned studies hold significant scientific importance in addressing the issue of GDP in coal mines worldwide.

The purpose of this work is the analysis of studies of crack formation in hazardous coal and establishment of the working range of dynamic load parameters during hydro-impulse impact for crack formation in the coal seam and changes in its stress-deformed state ahead of the face of the development drift.

## 2. Methods

The following methods were used during the analytical and experimental research: theory of strength of materials in order to establish their limit state and destruction; theory of coal, rock and gases outburst; analysis of theoretical and experimental studies of changes in the rate of deformation in coal with respect to the modulus of elasticity $3{\cdot}10^2$ MPa $\le E \le 5{\cdot}10^2$ MPa; experimental-statistical method of calculation and method of calculating the parameters of the cavitation generator.

## 3. Experimental studies of factors affecting the state of the coal-gas system

The main goal of measures to prevent the GDP is to reduce the impact of external factors on the coal-gas system. This task is solved either by reducing the intensity of coal mining, or by eliminating the gas-dynamic factor. With the intensification of the technological process of coal mining, the solution to the problem of coal mining is possible only by reducing the SDS of the rock massif, active action on the coal-gas system and monitoring its condition [2, 3, 6].

In rock mechanics, it is practically impossible to take into account all factors of external action on the coal-gas system when solving the engineering problems of the prevention of GDP (see Fig. 1). Therefore, from the entire list, one or two primary factors are singled out. For example, in the energy-force theory of sudden outburst of coal and gas, the set of parameters related to the gas-dynamic factor is characterized by the release energy, and the mining pressure and properties of the coal seam are characterized by the force of action [13].

Taking into account the factors of man-made action, we take the SDS of the coal-gas system as the dominant one, and any technological process that can lead to the initiation of GDP as a complementory one. The probability of the initiation GDP depends on the energy potential of the coal-gas system and the rate of gas pressure drop in the cracks of the coal seam.

Based on this, the main task of the complex of measures to prevent GDP is the formation of additional cracks for free gas filtration. Solving this issue is of particular importance in conditions where coal seams have low permeability and are in a stressed-deformed state.

When water is injected into the rock mass, the formation or development of existing cracks begins along the contour of the filtering part of the well, therefore, in all theoretical works, it is assumed that the development of cracks is determined by the stress state formed around the well. In the vast majority of works, for example [14–17], the stress state around the well is described by two components directed perpendicular to its axis ($\sigma_x$, $\sigma_y$) or ($\sigma_r$, $\sigma_\theta$). When solving problems for a plane in the form of a circular hole compressed at infinity in two directions by uniformly distributed loads, the vertical and horizontal components of the rock pressure ($\sigma_1$, $\sigma_2$) are determined. The third stress component $\sigma_z$, directed along the axis of the well and parallel to the rock pressure component $\sigma_3$, is usually not taken into account or is determined by simplified methods [14].

The value of the axial stress on the lateral surface of the well is estimated in [15]. The orientation of the developing crack was investigated during hydraulic fracturing of oil and coal seams [16]. When crossing the processing zone of the massif with workings, it was established that the opening of hydraulic fracturing cracks is observed at a distance of up to 100 m from the wells. Crack opening ranged from 1 mm to 20 mm. Directly near the well itself in the area of hydroperforation, there is an increased number of cracks of various orientations, as the distance from the well is reduced, the number of wide cracks decreases [17].

According to the normal separation criterion, it is noted that the development of the crack occurs in the plane of the maximum tensile stress. The modulus of elasticity of coal *E* along the layering, since it is in this direction that the dynamic action leads to the formation of cracks, is in the range from $3 \cdot 10^2$ MPa to $5 \cdot 10^2$ MPa. The coal seam has minimal resistance to the development of cracking under tensile stress. Tensile strength is approximately 30 times less than compressive strength and ranges from 0.1 to 1.0 MPa. Therefore, it can be assumed with high accuracy that the development of cracks will occur at injection pressure equal to the horizontal component of the rock pressure. Given this, it should be expected that the fracturing pressure due to its minimum component should be quite strongly related to the rock pressure. However, in practice there is no such strong connection. This is confirmed by the data of mine observations on the activity of the acoustic emission of the seam. Research determined that the spread of hydraulic fracturing pressure values is in the range from 0.5 to 1.2 $\gamma H$ [18].

The process of crack formation is also considered in the theoretical foundations of the development of methods and technical means of preventing sudden outbursts of coal, rock and gas. For example, in the generally recognized energy theory of sudden coal and gas outbursts, the main source of energy for the development of a fracture crack is the free, desorbed gas. The factor preventing destruction is the stability of the marginal part of the near-cut part of seam. In turn, the stability of the seam depends on the magnitude of rock pressure and the physical and mechanical properties of coal, the forces of internal and external friction. It was established that at a stress of more than 20 MPa, the energy of elastic deformations can be compared with the energy of free gas located in a coal seam with a methane content of 20 $m^3/m^3$ [13]. Such stresses can occur in near-cut part of seam, close to the surface of the hole. If the deformation energy is not absorbed by the massif, a crack develops and the coal block collapses.

Thus, the development of a crack in the near-cut part of seam can occur if the energy of deformations does not have time to be absorbed by the massif due to low frictional energy consumption. At the same time, the frictional energy consists of internal friction of coal and external friction with rocks of the roof and soil of the seam.

The next factor that initiates cracking is the process of stress redistribution in the massif. Rocks under the action of additional stresses and deformations are in an excessively stressed and deformed quasi-static state. The limit state of the coal-gas system is characterized by: the state of limit equilibrium of vertical and horizontal components of rock pressure; the tense state of the massif, its physico-mechanical and strength properties; cracked and porous structure of the coal seam; by the forces of contact (external) and internal friction.

In order to describe the limit state of materials and reveal the nature of their destruction, more than 40 theories of strength were developed, but only five of them are recognized as classical [19]: the theory of strength of maximum normal stresses by H. Galileo (I theory of strength); E. Mariotte's theory of strength of maximum linear deformations (II theory of strength); theory of strength of maximum tangential stresses by C. Coulomb (III theory of strength); M. Huber's energy theory of strength (IV theory of strength); Mohr's theory of strength (V theory of strength).

By their nature, the first two theories refer to the gap hypothesis, the third and fourth - to the shift, and the fifth - to the gap and the shift.

Coulomb's and Mohr's theories are most widely used in rock mechanics. The criterion of the Coulomb theory is the fluidity condition. For rocks, Coulomb introduced the functional term $\mu\sigma_\alpha$,, where $\mu$ is the coefficient of internal friction, $\sigma_\alpha$ is the normal stress acting on the sliding surface. A distinctive feature of this theory is the development of maximum effective tangential stresses taking into account internal friction. The load-bearing capacity of a coal seam is determined by contact and internal friction, which, when reduced, creates a system of cracks in the coal seam.

It is considered that the advantage of Mohr's theory is the possibility of its application, both as a criterion of strength under tension, and to take into account the fluidity of the material. It makes it possible to explain the different resistance of the material to destruction, which is observed in experiments with rocks during stretching and compression. However, the research works [14] denote that the theories of Coulomb and Mohr can satisfactorily describe the strength of rocks in compression, but are unsatisfactory in tension.

It is now generally accepted that contact friction plays a certain role in the process of rock destruction, but the question of the degree of its influence on the mechanism of destruction remains open. The action of vertical stresses is quite well studied, but the method of calculating horizontal stresses has a list of significant shortcomings. Moreover, the effect of normal horizontal and contact tangential stresses on the failure mechanism has not also been researched considerably.

As we can see, in a coal-bearing massif, the process of initiation and development of a crack in the heading part of a hazardous coal seam is influenced by a significant number of factors. At the same time, they are all interconnected. Therefore, it is necessary to identify the factors, the combination of which can lead to the process of destruction of the coal seam:

- the force of any mechanical action (in our case, high-pressure liquid injection);
- the forces of rock pressure and gas accumulated in the massif;
- shear processes during stress redistribution in the massif.

Taking into account the above, let's consider the relationship between the properties of coal in the zones of its transformation when the supporting rock pressure changes ahead of the face of the mining (Fig. 2). The figure also shows the schematic diagram of the location of the filtration part of the well relative to the maximum of the reference pressure zone.

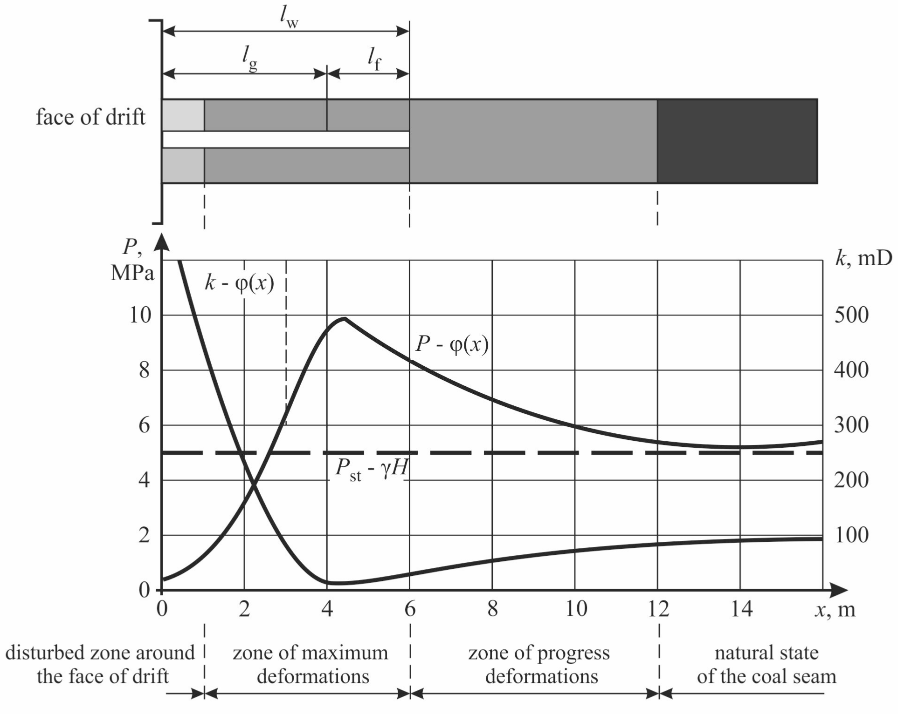



Figure 2 – The scheme of the impact of man-made factors on the SDS of the near-cut part of seam in the development drift

In the conditions of great depths, the permeability of coal is significantly reduced, and in the zone of maximum deformations in front of the working face, it equals almost zero. Therefore, the location of the filtration part of the well in the depth of the massif relative to the maximum of the support pressure zone has a significant impact on the effectiveness of hydraulic fracturing and the depth of sealing relative to the working face.

Wells with a length ($l_{well}$) of 6–8 meters are used during hydraulic fracturing of coal seams in the face of preparatory development which makes it possible to place their filtration part ($l_f$) at the maximum of the support pressure zone, where the filtration properties of coal gradually increase. At the same time, the process of cracking along the layer thickness is insignificant because the water under pressure either moves through layering cracks in the depth of the massif or squeezes out the part of the coal along with the sealed part of the well ($l_g$). In both the first and second cases, hydraulic loosening is considered effective based on the injection pressure drop. However, the volume of cracks is insufficient for effective degassing of the massif. Therefore, even after hydroflocculation or during its process, the danger of the manifestation of GDP remains [7].

**4. Research results of the crack formation process during hydro-impulse impact**

The use of hydraulic fracturing of coal seams for many decades has shown that fracturing is the primary purpose of fluid injection into coal seams. Over a long period of research, a large amount of data has been accumulated on the parameters and efficiency of liquid injection for dust suppression, degassing, and prevention of GDP. However, the crack formation process is still understudied. In practice, it is impossible to control the formation of cracks when injecting liquid into the massif. Therefore, theoretical studies and visual observations in industrial conditions determine the essence and mechanism of the crack formation process in these conditions.

In the process of hydroprocessing research, the hydraulic parameters of injection and liquid filtration through cracks to the open surface of the production or into adjacent wells are mainly considered.

There is a practice of using cavitation generators during hydraulic action on a coal seam [9, 20]. The results of studies of hydro-impulse loosening indicate intensive cracking in the coal mass around the filtering part of the well. The development of deformation and crack formation processes is accompanied by intense gas outburst and the squeezing of coal layers into the overlying rocks of the coal seam roof.

It is known that the fracturing process intensity depends on the rate of deformation development, which is determined by the expression $\acute{\varepsilon}=d\varepsilon/dt$ [21]. It has also been determined that a sharp decrease in coal strength occurs in the deformation rate range from 1 to 10 $s^{-1}$. If the rate of development of deformations is 10 $s^{-1}$ or more, then shear failure of coal is initiated in the strata.

The paper [9] gives the results of measuring the impulses of cavitation self-oscillations and compares them with the modulus of elasticity of coal $3\cdot10^2$ MPa$\leq E$

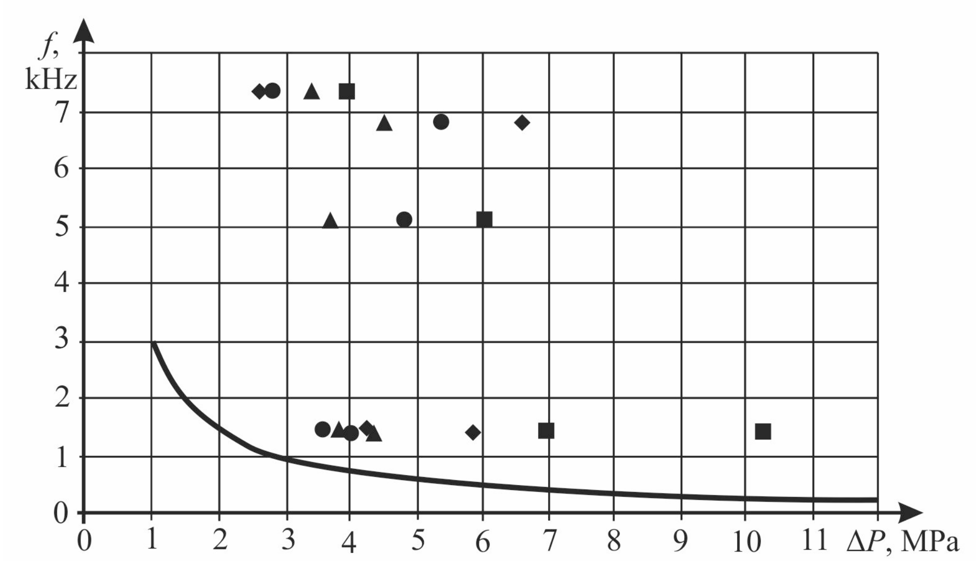
$\leq 5 \cdot 10^2$ MPa. Then, when an impulse load is applied by [21], the rate of development of deformations is determined by the expression [9]

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{\Delta P \cdot f}{E},$$

where $\dot{\varepsilon}$ – linear deformation of coal, $s^{-1}$; $\Delta P$ – impulse pressure, MPa; $f$ – impulse frequency, $s^{-1}$; $E$ – modulus of elasticity of coal, MPa.

Under the condition of development of the limit rate of deformation $\dot{\varepsilon} = 10\ s^{-1}$, the frequency of passage of pressure self-oscillation impulses during hydro-impulse loosening should correspond to the expression $f$=10$E/\Delta P$. According to this expression, the dependence of the frequency of pressure impulses passage on their magnitude, the generator's amplitude-frequency characteristic (AFC), was determined [9]. The research was carried out for four modes of hydro-impulsive action at injection pressure values of 5, 10, 20, and 30 MPa, respectively.

In our research, we consider the experimentally established values of frequency and pressure impulses concerning the limit value of the elasticity modulus $E$=3·10$^2$ MPa and the rate of deformations development $\acute{\varepsilon}$=10 $s^{-1}$ (Fig. 3), established at $P_н$ =5 MPa. If it is established that the conditions for crack formation are met in the mode with the lowest pressure (5 MPa), then all other modes will be more effective.




Curve – theoretical dependence of the impulse frequency $f$ on the value of the pressure $\Delta P$ at $\acute{\varepsilon}$=10 $s^{-1}$ and the modulus of elasticity of coal $E \geq 3 \cdot 10^2$ MPa
Points – experimental measurement points in the well simulator at a distance from the generator, respectively:
■ - 0.5 m; ● - 1.0 m; ◆- 1.5 m; ▲ - 2.0 m
Figure 3 – Comparison of the results of theoretical and experimental studies of impulse loading of coal seams

The results analysis of the theoretical and experimental data comparison shows that all values of impulses of self-oscillations of liquid pressure are above the curve of the limit rate of deformation development $\acute{\varepsilon}$=10 $s^{-1}$ at the value of the elasticity of coal modulus $E \geq 3 \cdot 10^2$ MPa. Therefore, conditions are created in the coal seam to initiate and develop shear deformations. Thus, it is sufficient to apply hydro-impulse action with an injection pressure of more than 5 MPa to initiate and develop the crack formation process in the coal seam. In this case, in the filtration section of the well, the dynamic load (pressure pulse) will equal $\Delta P \geq 3$ MPa and impulse frequency – $f \geq 0.8$ kHz.

In addition to the above, it is worth adding that coal has many surface defects in the form of pores, blebs, fractures, and cracks. The presence of these defects always leads to the concentration of maximum tangential stresses. As a result of high-frequency self-oscillations of liquid pressure impulses, there is a jump-like change in these stresses, which initiates the development of shear cracks at angles from 0 to $\pm \pi/4$ to the layering surface of the coal seams. At the same time, an increase in coal shear resistance and a decrease in friction coefficients contribute to an increase in the development angles of maximum tangential stresses up to $\pm \pi/4$. This relationship makes it possible to use the shear resistance of coal, that is, the resistance of coal to the penetration of liquid into the strata, as well as the force of internal friction, as criteria for controlling the pressure of liquid injection during hydro-impulse impact.

## 5. Conclusions

The following has been determined based on the analysis of theoretical and experimental studies of the factors that initiate the formation of cracks in the coal seam.

1. In the heading part of a hazardous coal seam, cracks develop during the redistribution of stresses in the massif under the influence of some mechanical action, the forces of rock pressure, and gas accumulated in the massif.

2. When applying hydro-impulse impact modes with an injection pressure of more than 5 MPa, pressure pulses of $\Delta P \geq 3$ MPa with a frequency of $f \geq 0.8$ kHz are created in the filtering part of the well which leads to the initiation and development of shear deformations, that is, to the initiation and development of cracking.

3. The use of the hydro-impulse loosening method allows the creation of a shear crack development zone around the well in low-permeability coal at various angles of inclination from 0 to $\pm\pi/4$ to the layering plane and, due to degassing, increasing the safe zone of coal extraction to the depth of drilling the well.

## REFERENCES

1. Saranchuk, V.I., Ayruni, A.T. and Kovalev, K.Ye. (1988), *Nadmolekuliarnaia organizatsiia. Struktura I svoystvo uglia* [Supramolecular Organization. Structure and Properties of Coal], Naukova dumka, Kiev, Ukraine.

2. Alekseev, A.D., Starikov, G.P. and Chistokletov, V.N. (2010), *Prognozirovanie neustoychivosti sistemy ugol-gaz* [Prediction of the Instability of the Coal-Gas System], Noulidzh, Donetsk, Ukraine.

3. Sobolev, V.V., Poliashov, A.S., Zberovskiy, V.V., Angelovskiy, A.A. and Chugunkov I.F. (2013), *Sistema ugol-gaz v uglevodorodakh ugolnogo genezisa* [The Coal-Gas System in Hydrocarbons of Coal Origin], Art-Press, Dnepropetrovsk, Ukraine.

4. Bondarenko, V.I., Vytiaz, O.Yu. and Zotsenko, M.L. (2015), *Hazohidraty. Hidratoutvorennia ta osnovy rozrobky hazovykh hidrativ* [Gas Hydrates. Hydrate Formation and Basics of Gas Hydrate Exploitation], Litohraf, Dnipropetrovsk, Ukraine.

5. Bulat, A.F., Skipochka, S.I., Palamarchuk, T.A. and Antsiferov, V.A. (2010), Metanogeneratsiia v ugolnykh plastakh [Methanogenesis in Coal Seams], Lira LTD, Dnepropetrovsk, Ukraine.

6. Ukrainian Ministry of Coal Industry (2005), *10.1.001740088-2005. Pravila vedeniia gornykh rabot na plastakh, sklonnykh k*

*gazodinamicheskim yavleniiam* [10.1.001740088-2005. Rules for Conducting Mining Operations in Strata Prone to Gas Dynamic Phenomena], Ukrainian Ministry of Coal Industry, Kiev, Ukraine.

7.Boyko, Ya.N., Nikiforov, A.V. and Rubinskiy, A.A. (2009), "Improving the Efficiency of Hydro-Dynamic Fracturing in outburst-hazardous Coal Seams in Preparatory Drift and Niches", *Zbirnyk naukovykh prats MakNII "Sposoby I sredstva sozdaniia bezopasnykh i zdorovykh usloviy truda v ugolnukh shakhtakh"*, no. 2 (24), pp. 52–57.

8. Bulat, A.F., Lukinov, V.V., Pimonenko, L.I., Bezruchko, K.A. and Burchak, A.V. (2012), Geologicheskie osnovy i metody prognoza vubrosoopasnosti uglia, porod i gaza [Geological Foundations and Methods for Predicting the Emission Hazard of Coal, Rock, and Gas], Monolit, Dnepropetrovsk, Ukraine.

9. Zberovskiy, V.V. (2012), "Active Methods of Hydraulic Impact on the Coal-Gas Massif", *Zbirnyk naukovykh prats NGU Ukrainy*, no. 37, pp. 40–47.

10. Sofiyskiy, K.K., Gavrilov, V.I., Zhitlenok, D.M., Vlasenko, V.V. and Petukh, A.P. (2015), *Gidrodinamicheskie sposoby vozdeystviia na napriazhonnye gazonasyschenye ugolnye plasty* [Hydrodynamic Methods of Impact on Stressed Gas-Saturated Coal Seams], Skhidnyi vudavnychyi dim, Donetsk, Ukraine.

11. Quangui Li, Baiquan Lin and Cheng Zhai (2015), "A new technique for preventing and controlling coal and gas outburst hazard with pulse hydraulic fracturing: a case study in Yuwu coal mine", *Natural Hazards*, no. 75, pp. 2931–2946, https://doi.org/10.1007/s11069-014-1469-9

12. Ge Zhu, Shimin Dong, Biao Ma (2022), "Pulse injection simulation based on the coupling of transient flow in tubing and fracture propagation in reservoirs" *Energy Science & Engineering*, vol. 10., no.4, pp. 1027–1565, https://doi.org/10.1002/ese3.1103

13. Petrosyan, A.P. (1978), Osnovy teorii vnezapnykh vybrosov uglia, porod i gaza [Fundamentals of the Theory of Sudden Outbursts of Coal, Rock, and Gas], Nedra, Moscow, USSR.

14. Stavrogin, A.N. and Protesian, A.G. (1985), Prochnost gornykh porod i ustoychivost vyrabotok na bolshikh glubinakh [Strength of Rock Strata and Stability of Drifts at Great Depths], Nedra, Moscow, USSR.

15. Filin, A.P. (1975), Pricladnaia mekhanika tverdogo deformiruemogo tela [Applied Mechanics of Deformable Solid Bodies], Nauka, Moscow, USSR.

16. Kulinich, V.S. and Kulinich, S.V. (2001), "Patterns of Rock Fracture by Hydraulic Fracturing", *Geo-Technical Mechanics*, no. 29, pp. 107–112.

17.Alekseenko, O.P. and Vaysman, A.M. (2003), "Calculation of the Steady-State Injection Rate of the Injection Well after Hydraulic Fracturing", *FTPRPI*, no. 3, pp. 23–31. https://doi.org/10.1023/B:JOMI.0000013781.70624.14

18. Ayruni, A.T. (1987), *Prognozirovanie i predotvraschenie gazodinamicheskikh yavleniy v ugolnukh shakhtakh* [Prediction and Prevention of Gas-Dynamic Phenomena in Coal Mines], Nauka, Moscow, USSR.

19. Tsimbarevich, P.M. (1948). *Mekhanika gornykh porod* [Rock Mechanics], Ugletekhizdat, Moscow, USSR.

20. Rodin, A.V. (1981), "Study of the Efficiency of Coal Mass Loosening with Pulsed Fluid Injection into the Seam", ", *Zbirnyk naukovykh prats* "*Novie metody razrusheniia i mekhaniki gornykh porod"*, Naukova Dumka, Kiev, pp. 22–25.

21. Lodus, Ye.V. and Romanovskiy, S.L. (1976), "The Influence of Strain Rate on the Strength and Fracture Toughness of Hazardous Coals and Rock Salt", *Zbirnyk naukovykh prats* VNIMI "*Gornoe davlenie i gornye udary"*, no. 99, pp. 151–154.

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## ЧИННИКИ ІНІЦІЮВАННЯ ТРІЩИНОУТВОРЕННЯ ПРИ ГІДРОІМПУЛЬСНОМУ РОЗПУШУВАННІ ВИКИДОНЕБЕЗПЕЧНОГО ВУГІЛЬНОГО ПЛАСТА

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**Анотація.** Стаття присвячена проблемі відпрацювання викидонебезпечних вугільних пластів на великих глибинах. Відомо, що при збільшенні глибини робіт у газонасиченому вуглепородному масиві при зміні його напружено-деформованого стану спостерігаються деякі особливості викидонебезпечного вугілля. Наприклад, спонтанне руйнування, зміна агрегатного стану та структури вуглеводневих з’єднань, зміна фільтраційних властивостей, тощо. Ці особливості мають місце при зміні деформацій стискання деформаціями розтягнення (зсуву). Існує перелік способів дії на масив для запобігання прояву газодинамічних явищ. Основною задачею цих способів є створення додаткових тріщин для ефективної фільтрації газу. Разом з цим при ведені гірничих робіт виникають техногенні чинники, що, створюють додаткове навантаження, змінюють структуру та властивості викидонебезпечного вугілля.

В роботі розглянуто чинники техногенної дії на привибійну частину вугільного пласта, які призводять до зниження ефективності способів попередження газодинамічних явищ. Розглянуто параметри процесів, що ініціюють розвиток тріщин навколо фільтраційної частини свердловини при імпульсному режимі нагнітанні рідини, при перерозподілі напружень в масиві, при саморуйнуванні вугілля у привибійній частині пласта. Розглянуто теорії міцності матеріалів з метою встановлення їх граничного стану і руйнування. Наведено результати теоретичних та експериментальних досліджень способу гідроімпульсного розпушування викидонебезпечного вугільного пласта. Досліджено зміни швидкості деформацій при імпульсному навантаженні вугілля відносно модуля пружності $3 \cdot 10^2$ МПа$\leq E \leq 5 \cdot 10^2$ МПа. Встановлено, що всі значення імпульсів автоколивань тиску рідини знаходяться вище кривої граничної швидкості розвитку деформацій $\acute{\varepsilon}=10$ с$^{-1}$ при значенні модуля пружності вугілля $E \geq 3 \cdot 10^2$ МПа. Зроблено висновок, що при гідроімпульсної дії з тиском нагнітання більш ніж 5 МПа у фільтраційної частині свердловини створюються імпульси тиску $\Delta P \geq 3$ МПа з частотою їх проходження $f \geq 0{,}8$ кГц. Це призводять до розвитку деформацій зсуву та ініціює розвиток тріщин по всій товщині вугільного пласта.

Дослідження гідроімпульсної дії були виконанні на шахтах Донецького вугільного басейну. Донбасу притаманні найбільш складні гірничо-геологічні умови, що складаються при відпрацюванні викидонебезпечних вугільних пластів.

**Ключові слова:** газодинамічне явище, гідроімпульсне розпушування, тріщиноутворення, система вугілля-газ.