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Development of a Hydrodynamic Method for Degassing of Gas-Saturated Flat-Lying Coal Seams

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Abstract: Deterioration of geological and mining conditions for underground extraction of coal deposits with increasing depth leads to significant gas release into mine workings, reaching 45 m^3 or more per 1 ton of coal mined at some mines. Existing standard methods for degassing of stressed coal seams often do not provide required degassing efficiency of 50 % and more for rhythmic operation of production faces. In some conditions, open-hole degassing efficiency of 30 % can be achieved, which allows to increase output per face up to 1,000 tpd with gas release from seam up to 5 m^3/min. However, at depths of 1,000–1,300 m and high-performance operation of longwall sets of equipment, gas release can reach 170 m^3/min that causes face stoppages due to gas hazard and slows down the pace of stope development and stoping. In addition, preliminary seam degassing requires rather long time. Modern achievements in the field of rock hydraulic fracturing are the basis for the development of low-energy safe and environmentally friendly technologies for degassing of stressed gas-saturated coal seams. The paper presents the findings of our studies on hydrodynamic action (HDA) on a gas-saturated flat-lying coal seam and the developed method for degassing and reduction of gas-dynamic activity of stressed coal seams in mine workings. Chemical interaction of some coal free radicals with water molecules and hydrolysis products has been revealed, resulting in formation of stable compounds. This leads to decreasing concentration of coal paramagnetic centers (PMC) and sorption activity. Our mine tests have for the first time found hydrodynamic effects on geotechnical and gas-dynamic processes in a coal mass during formation of a zone of intense gas release. Technology and layout for hydrodynamic action-based degassing of gas-saturated flat-lying coal seams have been developed, providing for spatial and time separation of seam degassing and coal extraction processes.

Keywords: boreholes, seam stress-strain state, hydrodynamic effects, coal seam degassing intensification, HDA parameters, stressed seam degassing layout.

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Разработка способа дегазации газонасыщенных пологих угольных пластов гидродинамическим воздействием

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Аннотация: Ухудшение горно-геологических условий подземной разработки угольных месторождений с глубиной приводит к значительному газовыделению в горные выработки, которое на отдельных шахтах достигает 45 $м^3$ и выше на 1 т добытого угля. Существующие нормативные способы дегазации напряженных угольных пластов часто не обеспечивают необходимой для ритмичной работы очистных забоев эффективности дегазации 50 % и выше. В некоторых условиях можно достичь эффективности скважинной дегазации 30 %, что позволяет увеличить нагрузку на лаву до 1 000 т/сут при газовыделении из пласта до 5 $м^3$/мин. Однако на глубинах 1 000–1 300 м при высокопроизводительной работе очистных комплексов выделение газа может достигать 170 $м^3$/мин, что приводит к остановкам забоев по газовому фактору и сдерживает темпы ведения очистных и подготовительных работ. Кроме того, предварительная дегазация пластов осуществляется довольно продолжительное время. Современные достижения в области гидроразрушения горных пород являются основой для разработки малоэнергоемких безопасных и экологически чистых технологий дегазации напряженных газонасыщенных угольных пластов. В статье приведены результаты исследований влияния гидродинамического воздействия (ГДВ) на газонасыщенный пологий угольный пласт и разработки способа дегазации и снижения газодинамической активности напряженных угольных пластов в горные выработки ГДВ. Установлено химическое взаимодействие части свободных радикалов угля с молекулами воды и продуктами ее гидролиза, в результате которого образуются устойчивые соединения, что приводит к снижению концентрации парамагнитных центров (ПМЦ) в угле, и соответственно к уменьшению сорбционного взаимодействия. Шахтными экспериментами впервые установлено влияние гидродинамического воздействия на протекание геомеханических и газодинамических процессов в угольном массиве при образовании зоны интенсивного газовыделения. Разработаны технология и схема дегазации газонасыщенных пологих угольных пластов гидродинамическим воздействием, предусматривающие разделение в пространстве и времени процессов добычи угля и дегазации пластов.

Ключевые слова: буровые скважины, напряженно-деформированное состояние пласта, гидродинамическое воздействие, интенсификация дегазации угольного пласта, параметры ГДВ, схемы дегазации напряженных пластов.

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Introduction

Increasing depth and intensity of mining is accompanied by increasing gas volumes in mines, leading to increasing costs and decreasing productivity and labor safety. The adverse dynamics of injuries from gas and dust explosions, various manifestations of gas-dynamic phenomena cause severe social and economic consequences [1–3].

In modern conditions, gas release from being extracted seams can reach 45 m^3/t and more. It is impossible to ensure high level of coal production without drastic reduction in gas release into mine workings, first of all, from coal seams. For cost-effective operation of a longwall set of equipment, methane drainage efficiency should be at least 50 %. The use of traditional methods of methane drainage and reducing gas-dynamic activity of coal seams based on drilling of methane drainage boreholes has sharply decreased with increasing mining depth due to decreasing the radius of borehole effect. Seam methane drainage efficiency can be slightly increased due to active impacts on gas-bearing coal seams, such as, for example, interval hydraulic fracturing, two-stage pumping of liquid, hydro-pulse treatment, etc. However, these local technologies are very rarely used due to the complexity of their implementation in constrained underground conditions, high probability of water breakthroughs into mine workings and, most importantly, the lack of time for painstaking and large-scale work [4–7].

Scientists of the IGTM of NAS of Ukraine have developed and introduced, at Donbass mines, environmentally friendly and energy-saving method of hydrodynamic action (HDA) on a coal seam by working fluid (water) that results in redistribution of rock and gas pressure, coal softening and, thus, methane desorption. On the basis of the approach, standards-compliant methods have been developed and introduced for opening outburst-prone coal seams by crossheadings and preventing coal-and-gas outburst in the lower part of webs extracted by header units [8].

Gas-saturated coal seam stress relief by hydrodynamic action results in increasing permeability, fracturing, and fracture joining into filtration channels through which free and adsorbed methane moves towards the borehole. Notice that in this case the adsorbed methane is contained in closed pores isolated from each other, and, in zones of maximum compressive stresses, the seam transforms into a disturbed structure of the V type, in which the pore radii are comparable to the sizes of the adsorbed molecules. Due to the hydrodynamic action, the coal seam is disintegrated and part of the coal is extracted from the coal-rock mass. This leads to decreasing load-bearing strength of the seam and weakening of interlayer contacts in the roof rocks that, when extracting the seam, ensures uniform (without delays) development of strains and eliminates manifestation of sudden coal-and-gas outbursts [9].

The main idea of this study is to use the revealed patterns of geomechanical and gas-dynamic processes during hydrodynamic action on a gas-saturated coal seam through underground boreholes and the features of the processes of gas release from the seam into underground mine workings after carrying out preventive work to determine effective parameters of the method of HDA on flat-lying coal seams and its implementation layout under mining conditions.

To achieve this goal, the following problems are being solved:

– studying the reasons for the insufficient effectiveness of the existing methods for a coal-rock mass methane drainage and justifying the prospects of the hydrodynamic action;

– revealing the patterns of geomechanical and gas-dynamic processes during hydrodynamic action on a gas-saturated coal seam through underground boreholes and the features of the processes of gas release from the seam into underground mine workings after carrying out preventive work;

– determining technological parameters of the HDA method for flat-lying coal seams and developing a promising process layout for coal seam methane drainage by hydrodynamic action.

The study methods. Analysis of the effectiveness of traditional mine methane drainage methods; laboratory, mine studies and commercial testing of the hydrodynamic method of coal seam methane drainage using the method of statistical data processing; mechanical and geophysical methods of mine instrumental measurements.

The study findings. The main methods of methane drainage, their disadvantages and advantages are described in detail in the works of A. T. Airuni, G. D. Lidin and other authors [10–13].

The performed analysis of the traditional coal mine methane drainage methods and means effectiveness showed that:

– further increasing the production face producibility is possible only if the problem of controlling gas-dynamic condition of f coal-rock mass is effectively solved;

– traditional methods of methane control in coal mines in situation of permanent intensification of mining operations and extraction shifting to ever deeper levels often can no longer provide both large coal extraction and safe working conditions. The effectiveness of seam underground methane drainage is limited by the value of gas drainage efficiency of 0.2 and can be slightly increased by conducting active actions on coal-gas bearing seam/series (for example, interval hydraulic fracturing, gas-hydro-pulsed action, etc.). However, these local technologies are very rarely used due to their implementation complexity in restrained underground conditions, high probability of water breakthroughs in mine workings and the lack of time for painstaking and large-scale work;

– hydrodynamic method of methane drainage gas-saturated flat-lying coal seams requires theoretical and experimental substantiating studies, as borehole as extensive testing in mine conditions.

Any, including technogenic, imbalance in the coal-gas system leads to diffusion, filtration, sorption-desorption processes and, most importantly, to methane generation in a coal seam [14]. The system destabilization is due to increase or decrease in pressure. In this case, the ratio of free and adsorbed gas changes. The adsorbed-free transition of gas (and vice versa) proceeds at different rates. Information on changing the kinetic parameters is of great practical value for coal seam methane drainage and decreasing its gas-dynamic activity.

The effect of hydrodynamic action on the degree of coal seam methane drainage was studied using electron paramagnetic resonance (EPR) method. The use of computer facilities during the experiments and signal recording allowed reaching much higher level of information content, accuracy, and reliability of the information obtained.

The experiments were carried out according to proven techniques, providing for recording superhigh-frequency energy absorption spectrum by paramagnetic centers (PMCs) of coal under normal conditions and at the moment of stabilization at increasing pressure to 6 MPa [15–18]. Using the EPR-PC system made it possible to record the transition process in time at high accuracy and survey its parameters.

The study of the kinetic parameters of coal-gas interaction was carried out on coal samples taken from seams l_4 of PJSC "Mine named after A.F. Zasyadko" and l_3^1 of Mine "Sukhodolskoe-Vostochnoe" in the process of applying the hydrodynamic action.

The transition process was approximated by the exponential law being characteristic of fast gas-dynamic processes in coal seams [19]:

$$I = I_{\text{исх}} - K_N\left(1 - e^{\frac{t}{T}}\right),$$

where I is integrated intensity of EPR spectrum of coal sample; I_{in} is integrated intensity of the initial EPR spectrum of the coal sample; K_N is passivation factor, which reflects the percentage of paramagnetic centers capable of interacting with the gas in the coal, %; t is current time, s; T is response time of the transition process, s.

The laboratory studies showed that hydrodynamic action results in decreasing concentration of paramagnetic centers in the treated coal approximately 3 times compared with the initial values. Hydrolysis of coal leads to rupture of various bonds and the component composition change. Cyclic mechanical effects result in rupture of bonds in the aromatic ring of a coal molecule. HDA obviously promotes coal interaction with water molecules and its hydrolysis products, resulting in forming stable that, in turn, leads to decreasing concentration of paramagnetic centers in the treated coal and, correspondingly, to decrease in sorption interaction (Table 1).

Thus, the hydrodynamic action affects the intermolecular mechanochemical interaction of coal and methane gas, the sorption properties of coal, and increases the coal fracturing that finally promotes the coal seam methane drainage.

Commercial-scale implementation of the hydrodynamic action method of methane drainage and reducing gas-dynamic activity of gas-saturated flat-lying coal seams l_4 of PJSC Mine named after A.F. Zasyadko and l_3^1 of Sukhodolskoe-Vostochnoe Mine are adequately covered in [20–22].

Table 1

Kinetic parameters of transient process of coal and gas interaction after HDA in l_4 seam (3rd western belt heading)

Sample No.	Volatile-matter yield V^{daf}, %	Ash content *A*, %	PMC co0ncentration $N^{a}\times10^{19}$, $г^{-1}$	Passivation factor K_N, %	Response time T_N, s	Limit sorption capacity Q, ml/g	Line width ΔH, E	Line width change $K_{\Delta H}$, %
592	33.20	1.24	3.79	35.5	94.7	9.96	7.2	4.3
593	30.15	2.91	3.24	38.1	61.7	9.13	7.4	9.0
594	27.33	3.72	3.70	37.0	79.3	10.13	6.8	13.2
595	29.17	2.00	3.34	35.2	81.4	8.70	7.5	5.1
596	31.15	1.50	3.94	35.2	94.7	10.26	7.4	5.4
597	28.20	3.00	3.43	37.5	72.1	9.52	7.2	6.5

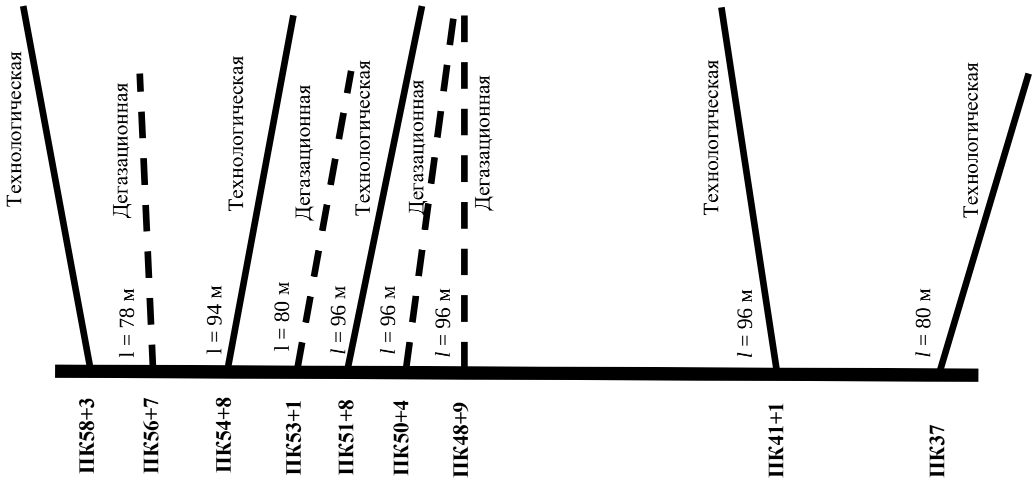

Fig. 1. Drilling pattern in the 23rd eastern inclined longwall

Fig. 2. Change in degassing borehole flow rate at Picket53+1 m after HDA

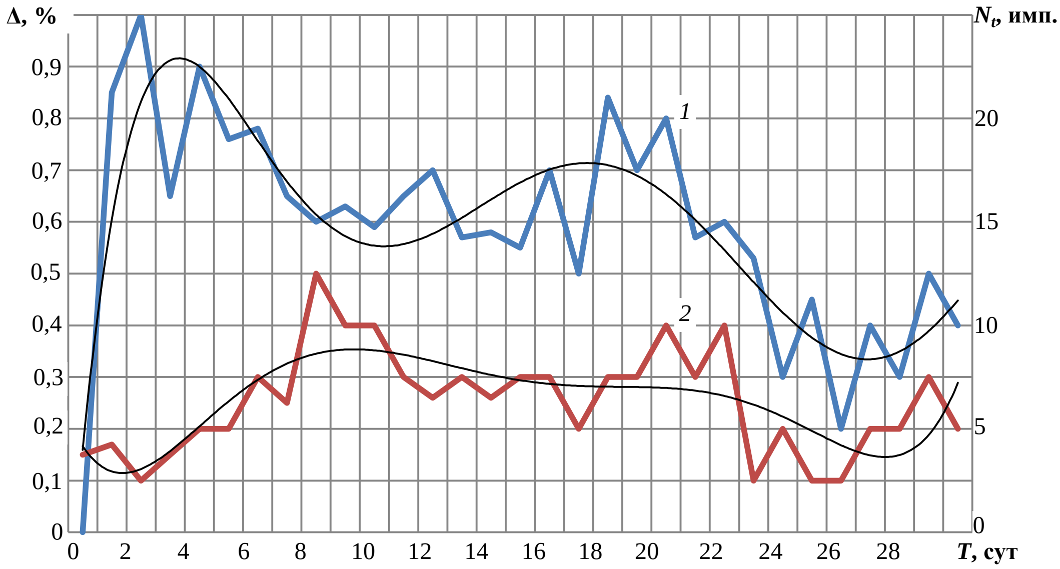

Fig. 3. Trends of geotechnical and gas-dynamic characteristics for l_1 seam in the process of HDA:
1 – acoustic emission; *2* – methane concentration increment

Five technological and four methane drainage boreholes were drilled in the conveyor drift of the 23rd eastern inclined longwall of the Sukhodolskoe-Vostochnoe Mine The layout of the boreholes is shown in Fig. 1.

Observations showed that during the operation of the underground boreholes, methane drainage through them is uneven. After hydrodynamic action, increased methane drainage is observed, which reaches maximum for 60–100 days, and then its gradual decrease occurs. Fig. 2 shows the results of measurements of a methane drainage borehole flow rate after HDA at various distances to a longwall.

After hydrodynamic action through a technological borehole, methane drainage in the methane drainage borehole gradually decreases, reaching minimum value when the longwall approaches 120-100 m of the borehole. This is explained by decreasing free methane content in the seam and the support pressure influence.

With further approach of the longwall to the boreholes, methane release through them gradually increases due to redistribution of rock pressure forces and development of an additional fracture system due to the collapse of the roof rocks.

Maximum values of methane release from the boreholes were recorded when the longwall was located at a distance of 15–20 m. After that, the methane release from the boreholes decreases until they cross the longwall face due to rapidly increasing volume of fractures connecting the boreholes to the longwall face, reducing the amount of free gas in the coal and the methane release directly into the longwall.

In total, more than 199 thousand m^3 of methane were released from the technological boreholes. The average life of such boreholes was 60 days at average flow rate of 416 m^3/day per borehole; the amount of methane released from one borehole was more than 25 thousand m^3.

Hydrodynamic action on a gas-saturated coal seam with periodic extraction of methane and a part of the disintegrated coal from underground boreholes leads to redistribution of stresses in the rock mass, which is described by the statistical characteristics of the dynamics of acoustic emission (AE) activity [23]. In turn, the change in the stress-strain state of coal and rocks has significant effect on the change in the gas release intensity [24].

The change in the geomechanical state of the coal-bearing mass was evaluated based on the acoustic emission using sound-detecting equipment (SCE). The seismic receiver installation method and its radius of action were determined according to [25].

Figure 3 shows the findings of monitoring the nature of changes in geomechanical and gas-dynamic processes in seam l_1 during three-time hydrodynamic action through the technological borehole drilled at Station42+5 m.

Analysis of the graphs shows the consistent dynamics of the processes in the individual areas. General trend to delay of the local maxima of the increase in methane concentration in relation to the AE local maxima is observed. For instance, in the first cycle, local maximum of the acoustic emission intensity was recorded on the third day, whereas local maximum of the methane concentration in the air stream in the working was recorded on the sixth day. Similarly, after the second action cycle, performed 15 days after the first action cycle, local maxima of the methane concentration and AE activity were recorded on the 17th and 21st days, respectively. After the third action cycle on the 24th day, local maxima of Δ and AE were recorded on the 27th and 28th days, respectively.

Thus, the investigations of HDA influence on the interaction of geomechanical and gas-dynamic processes (in the same mining and geological conditions) showed time lag of the local maxima of methane concentration in relation to the acoustic emission maxima by 1–5 days. The HDA effect on the processes is described by a sextic polynomial.

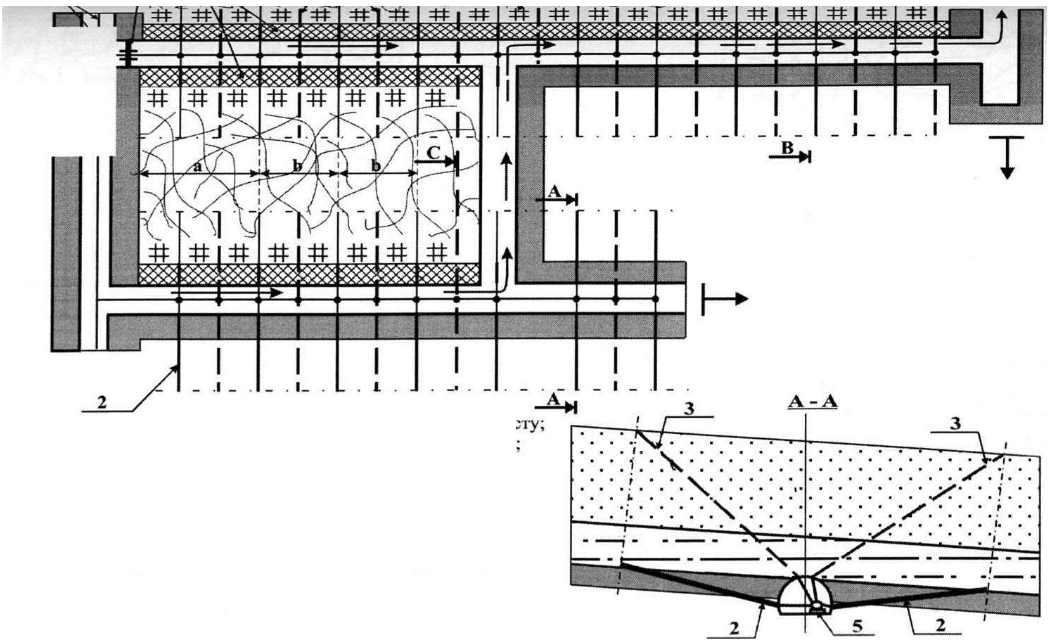

Fig. 4. Arrangement of flat-lying coal seam degassing using hydrodynamic action
1 – separating strip; *2* – degassing borehole in a seam; *3* – degassing borehole in host rock; *4* – air governor; *5* – gas pipeline; *6* – cages; *a* – initial spacing of main roof breaks; *b* – spacing of main roof breaks;
—– direction of intake air; – – – – direction of return ventilation air

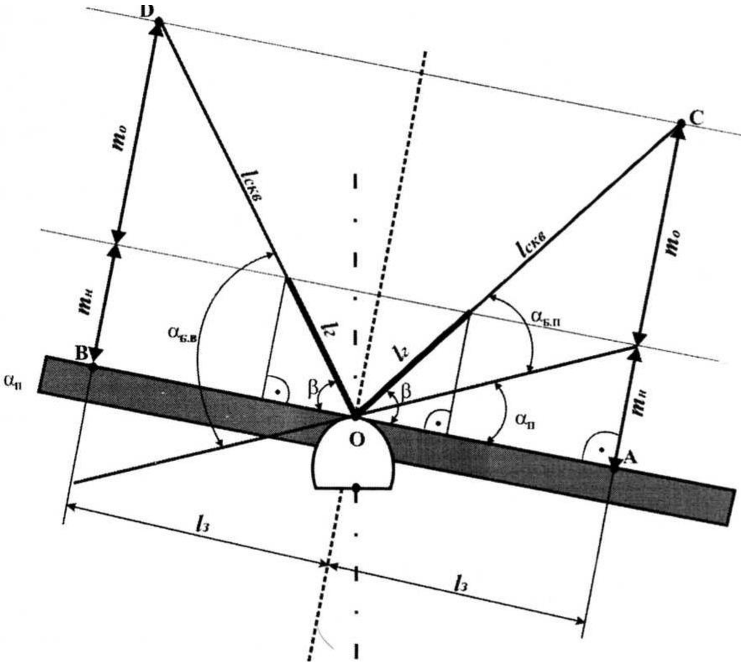

Fig. 5. Calculation pattern for degassing borehole parameter determination

Based on the analysis of the conditions for extraction of gas-saturated coal seams and the studies findings, the promising Process Flow Schematic (PFS) for seam methane drainage using the hydrodynamic action was developed. The PFS provides for drilling, from development workings or special niches, of technological boreholes for coal and methane drainage boreholes for rock (Fig. 4).

Borehole drilling into a coal seam shall be performed through the bottom rocks. The length of the rock part of the borehole should be at least 10 m. The technological borehole parameters are determined graphically taking into account the seam thickness and dip angle, the distance to the point of maximum support pressure, and the distance from the working bottom to the borehole collar. Drilling of methane drainage boreholes is performed through the roof rocks. The length of sealed part of the methane drainage borehole is determined by its length in the immediate roof rocks, but should be at least 6 m. The methane drainage borehole drilling parameters are determined by calculations (Fig. 5).

The angle between the seam roof and the methane drainage borehole

$$\beta = \operatorname{arctg}\frac{m_о + m_н}{l_з},\ \text{degrees},$$

where $m_о$ – the basic roof thickness, m; $m_н$ – the immediate roof thickness, m; $l_з$ – distance to the zone of maximum support pressure, m.

Borehole length:

$$l_{скв} = \sqrt{(m_о + m_н)^2 + l_з^2},\ \text{m}.$$

Methane drainage borehole angle up the plunge:

$$\alpha_{б.в} = \beta + \alpha_п = \operatorname{arctg}\frac{m_о + m_н}{l_з} + \alpha_п,\ \text{degrees},$$

where $\alpha_п$ – seam dip angle, deg.

Methane drainage borehole angle to the dip:

$$\alpha_{б.п} = \beta - \alpha_п = \operatorname{arctg}\frac{m_о + m_н}{l_з} - \alpha_п,\ \text{degrees}.$$

Depth of sealing of methane drainage borehole:

$$l_г = \frac{l_н}{\sin\beta},\ \text{m}.$$

After borehole casing with steel pipes 102–114 mm in diameter and sealing it, the modified ZVD200/4 gate valve with control mechanism and a remote control panel is installed on the casing mounting flange. The hydrodynamic action parameters are given in Table 2.

Table 2

Parameters of the method for flat-lying coal seam degassing intensification

Item	Quantity
Methane drainage borehole diameter, mm	≥ 76
Methane drainage borehole diameter in sealed part, mm	≥ 150
Methane drainage borehole length within coal, m	≥ 20
Methane drainage borehole length within rock, m	Calculated
Depth of sealing of methane drainage borehole, m	≥ 6
Fracturing fluid feed pressure, MPa	≤ 5
Residual pressure in the borehole after pressure relief, MPa	0
Volume of liquid discharge in the end of each cycle, m^3	0.3–1.0
Coal recovery factor	≥ 0.01
Efficiency of methane drainage	0.3-0.8

When the ZVD200/4 gate valve is closed, the main pump feeds water through the borehole into the coal seam until the working pressure is reached, then the gate valve opens and the pressure is released to the value that determines the required pressure difference in the seam. As a result, water is discharged from the borehole along with the ruptured coal and free and desorbed gas (methane). The cycles of pressure rise and relief are repeated until the particles of the ruptured coal are thrown out the borehole or when the required amount of coal and gas extracted from the treatment zone is reached. After HDA completion, the flange of the corrugated gas outlet hose of the methane drainage system is installed on the mounting flange of the casing.

Conclusions

As a result of the mine research of the method for methane drainage of gas-saturated flat-lying coal seams by hydrodynamic action, the following is established.

1. The currently used standard methods for methane drainage of gas-saturated coal seams at great depth often do not provide required methane drainage efficiency of 50% and more to ensure rhythmic operation of production faces. This results in decreasing rate of development and stoping work.

2. For the first time, the influence of hydrodynamic action on the degree of methane drainage of gas-saturated seams was revealed. Effect of pressure decreases the content of active paramagnetic centers (capable of interacting with methane) in coal that, in turn, decreases boundary sorption capacity of the coal substance. To evaluate the duration of sorption and desorption interactions in coal – gas system, it is proposed to use the transient process time indicator T_N, which characterizes the substance fracturing (broken condition).

3. The synchronous nature of the change in geomechanical and gas-dynamic behavior of coal seam after the hydrodynamic action (HDA) was established. Our studies showed time lag of the local maxima of methane concentration in the working air stream in relation to the acoustic emission maxima by 1–5 days.

4. Intensive gas release from underground boreholes after HDA is affected by the temporary support pressure of the approaching longwall. As the longwall approaches, methane flow rate of the boreholes initially decreases, and then increases sharply, reaching maximum at the distance of 25-15 m from the boreholes. Later, during underworking of the boreholes, the methane release from them decreases due to methane release immediately into the longwall and mined-out space.

5. The technology and method for intensifying methane drainage of flat-lying gas-saturated coal seams have been developed; the method parameters allowing achieving methane drainage efficiency of 30–70% in the treated areas have been determined.

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