ORIGINAL PAPERS

DOI: 10.17073/2500-0632-2019-2-122-131

Assessment of Effectiveness of Methods and Techniques for Degassing Methane-containing Coal Seams

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Abstract: The findings of review of promising methods and techniques providing increasing effectiveness of degassing of coal seams containing methane in the process of their underground mining are presented. Based on the review findings, traditional methods and techniques of degassing were identified, the effectiveness of which is 12–25 %, as well as unconventional methods providing methane degassing of up to 40%. As a classification feature of the unconventional methods and techniques of gaseous methane liberation, a condition of decreasing pressure and increasing temperature of coal matrix containing solid gas hydrate has been adopted. The conditions for methane transition from gas hydrate to free gas taking into account actual mining and technogenic conditions of the mines have been identified. Given the difficulty of supplying additional thermal energy into a coal seam, as the main way to reduce pressure in the seam, unloading of the rock mass relative to the initial stress state, and disruption of coal and rocks in the course of transition from their elastic deformation to elastic-plastic and out-of-limit deformation are accepted.

Keywords: coal seam, methane, colliery, degassing, gas hydrate, rock pressure, desorption, filtration, rock disruption, gas content, coal matrix.

For citation: Shirjaev S. N. Assessment of effectiveness of methods and techniques for degassing methane-containing coal seams. *Mining Science and Technology*. 2019;4(2):122-131 (In Russ.). DOI: 10.17073/2500-0632-2019-2-122-131.

Оценка эффективности способов и средств дегазации углеметановых пластов

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Аннотация: Представлены результаты анализа перспективных способов и технических средств, обеспечивающих повышение эффективности дегазации углеметановых пластов при их подземной разработке. По результатам анализа выделены традиционные способы и средства дегазации, эффективность которых составляет 12–25 %, и нетрадиционные способы с эффективностью десорбции метана до 40 %. В качестве классификационного признака нетрадиционных способов и средств десорбции метана газа принято условие снижение давления и повышение температуры угольной матрицы твёрдого газового гидрата. Выявлены условия перехода метана из газогидратного состояния в свободное с учётом реальных горнотехнических и техногенных условий шахт. Учитывая сложность подачи дополнительной тепловой энергии в угольный пласт, в качестве основного способа снижения давления в пласте принята разгрузка массива горных пород относительно исходного напряжённого состояния и дезинтеграция угля и пород при переходе от упругого их деформирования к упруго-пластичному и запредельному.

Ключевые слова: угольный пласт, метан, шахта, дегазация, газогидрат, горное давление, десорбция, фильтрация, дезинтеграция пород, газоносность, угольная матрица.

Для цитирования: Ширяев С. Н. Оценка эффективности способов и средств дегазации углеметановых пластов. *Горные науки и технологии*. 2019;4(2):122-131. DOI: 10.17073/2500-0632-2019-2-122-131.

Introduction

Coal deposits in Russia and abroad, as a rule, are highly methane-bearing, and during their development, an average of 18.6 m^3/t of methane is produced per tonne of coal mined [1–3] that is a limitation of the productivity of modern highly productive equipment. The abundant release of methane into mine workings at a certain combination of geological, mining, and organizational factors leads to incidents and dangerous production gas-dynamic situations in the form of gas pollution of mine workings, explosions of methane-air mixtures.

Effective management of the interacting technological, geomechanical and gas-dynamic processes in a modern coal mine requires solving a set of scientific and practical problems, including the development and implementation of mine process flow sheets that are adaptive to wide range of geological, geotechnical, and mining conditions of coal deposits and operating modes of high-performance mining facilities.

The work of many scientists and practitioners has been devoted to the development and implementation of high-performance technologies for the preparation and development of methane-bearing coal seams. However, the main urgent problems have not yet been solved: theoretical studies on the release (desorption) of methane have not been brought to practical use (efficiency of gas drainage of 0.12–0.40 has been achieved); the role of methane in a sudden coal burst as a complex physical-chemical-mechanical phenomenon has not been unambiguously identified; the parameters of methane breakthroughs from satellite seams, geological dislocations, and worked-out space have not been determined. A promising way for increasing the intensity of methane release from coal, including from the gas-hydrate state, is the creation and implementation of active combined degassing methods, providing for stage-by-stage coal disintegration and decreasing rock pressure.

In this regard, the need has arisen for the creation and implementation of active combined methods and means of phased degassing of an inhomogeneous coal-rock mass and worked-out space to ensure efficient and safe underground mining of highly gas-bearing coal seams. To this end, the effectiveness of traditional technologies for methods and means of degassing methane-bearing coal seams was assessed with the aim of developing, substantiating the parameters and introducing active combined methods and means of multi-stage degassing of an inhomogeneous coal-rock mass and the worked-out space for efficient and safe mining of methane-bearing coal seams.

The main idea of creating active combined methods and means of multi-stage degassing of methane-bearing coal seams consists in using the identified patterns of interaction of technological, gas-dynamic and geomechanical processes in a coal-rock mass to control the coal matrix disintegration, reduce pressure in it, and ensure the transition of methane from a hydrated state to gaseous one taking into account real mining conditions at mines.

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

– the synthesis of alternative options of active combined methods for the artificial disintegration of coal seams for their multi-stage degassing;

– identification of the patterns of methane desorption in wide range of mining and geological conditions of coal mines based on the results of mine research;

– identification of effective variants of active combined methods of multi-stage degassing of an inhomogeneous coal-rock mass based on the results of computer simulation and mine experiments;

– substantiation of technological parameters and the implementation of active combined methods and means of multi-stage degassing of high-gas-bearing coal seams.

The research methods. Analysis of the effectiveness of traditional methods and means for mine degassing; mine experiments; computer simulation of interacting technological, gas-dynamic and geomechanical processes; statistical assessment and ranking of options for active combined multi-stage degassing methods; synthesis of process flow options for the preparation and development of gas-bearing coal seams.

The study findings. Based on the analysis of the effectiveness of traditional methods and means of coal seam degassing [1, 3-5, etc.], the following was found:

– the annual volume of methane recovered in the period 1990–2009 in the Kuzbass by means of degassing amounted to 60–330 mln m^3, gas suction, 120–410 mln m^3, ventilation, 470–600 mln m^3;

– the proportion of mines which applied seam degassing in the period of 1990–2009 in the Kuzbass amounted to 0.18–0.33; work-out space degassing, 0.21–0.28; gas suction, 0.28–0.39;

– the effectiveness of degassing at the Kuzbass mines is 3–44 % and does not exceed 28 % on average,

– combined degassing methods are most effective. For example, the simultaneous use of gas suction and degassing allow achieving efficiency of gas drainage of 0.55, whereas degassing under similar conditions only provides 0.28;

– the use of combined ventilation schemes ensures the achievement of efficiency of gas drainage of 0.55;

– the use of boreholes drilled from the earth's surface ensures maximum methane drainage: efficiency of gas drainage reaches 0.85, whereas that for seam degassing under the same conditions provides 0.20 only.

The presented methane drainage indicators for different methods confirm not only the relatively low efficiency of the methods and means of methane-bearing coal seams degassing, but also the lack of methods for predicting methane release parameters in specific mining & geological and geotechical conditions, since the design and actual values of efficiency of gas drainage differ by 2–3 times. To develop new methods for predicting degassing parameters, it is necessary to identify and use the patterns of methane adsorption and desorption, the disintegration of coal matrix under the influence of pressure and temperature above the equilibrium parameters of gas hydrates that ensures the change of methane from hydrate to gaseous state, taking into account the actual mine conditions.

The following impacts on a coal mass are considered as alternatives to active combined methods of multistage degassing of an inhomogeneous coal-rock mass: electropulsed, periodic plasma-pulsed, vibrovawe, disintegration by fluid, vacuum degassing, etc. [6, 7, 11, 12]. The theoretical foundations of the coal matrix formation are described in [10, 13, 16]. According to the findings of these studies, methane gas in a coal seam can be in three forms: free gas in the pore and fracture spaces of coal or rocks; methane in adsorbed or gas hydrate state. Gas hydrates are solid crystalline substances, containing water and gas molecules.

Phase equilibrium diagram of solid coal-gas solutions (SCGS) containing methane is presented in Fig. 1.

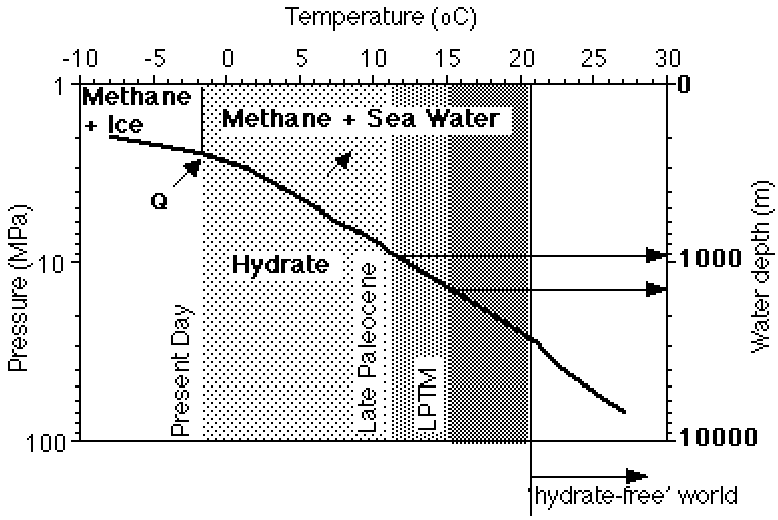

Fig. 1. Phase equilibrium diagram of methane in coal matrix [18]

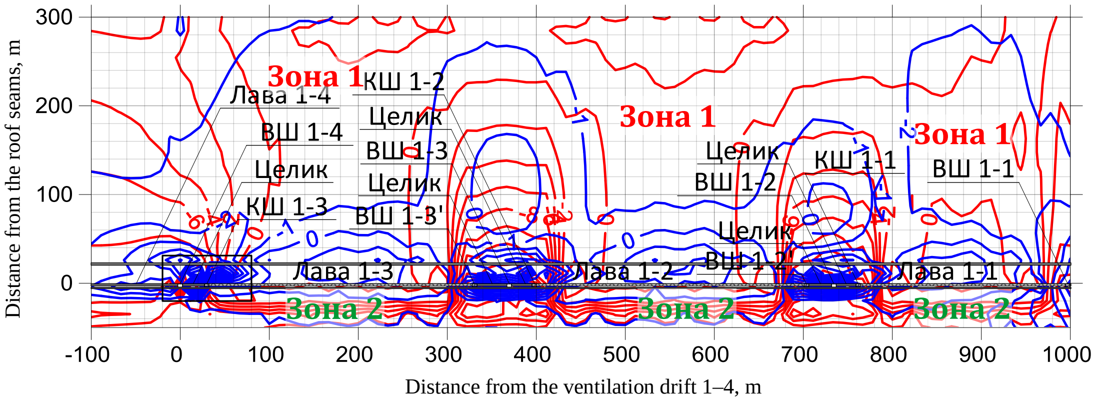

Fig. 2. Vertical (red lines) and horizontal (blue lines) stresses (MPa) in the zone of influence of goaf of three extraction districts

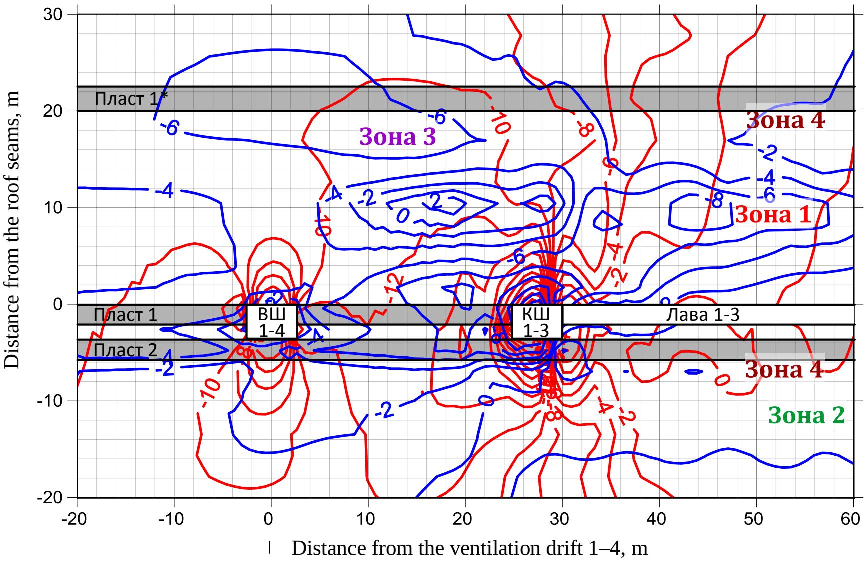

Fig. 3. Vertical (red lines) and horizontal (blue lines) stresses (MPa) in the zone of influence of goaf of three extraction districts, a portion of Fig. 2

According to the diagram, the transition of methane from solid coal-gas solutions and the adsorbed state to a gaseous state is possible at decreasing pressure and increasing temperature of the coal matrix. The possibility of increasing temperature of coal seams is limited in the mine by fire safety requirements and sanitary rules [19, 20]. Therefore, the main parameter providing the intensification of the methane transition to the gaseous state is reduction of mechanical stress, which is accompanied by the decomposition of solid coal-gas solutions (SCGS) and increasing methane pressure in natural and man-made fractures. There are several hypotheses for the transition of methane to the gaseous state and its migration through fractures and pores. However, the efficiency of these mechanisms realization in practice is not always confirmed [5, 9, 11, 12, 14–16].

Fig. 2 shows the results of numerical simulation of the distribution of vertical and horizontal stresses after mining-out three extraction districts in the conditions of the Yerunakovsky deposit in the Kuzbass. The thickness of the mined seam 1 is 2.48 m, that of undermined seam 1* (in the mined seam bottom) and seam 2 (in the mined seam roof) for the simulation is taken to be 2 m.

Fig. 3 shows a fragment of Fig. 2 in the form of a cutout on a large scale with the purpose of detailed description of the nature of the stress distribution in the rock mass near the ventilation drift 1–4, conveyor drift 1–3 and the stope worked-out space of extraction districts 1–3. The signs of stresses in Fig. 2 and 3 are as follows: compression $\sigma < 0$; tensile $\sigma > 0$.

According to the results of the analysis of vertical and horizontal stresses in the rock massif under the mutual influence of the worked-out space of several adjacent extraction districts separated by coal pillars, the following zones were identified, within which we should expect decreasing mechanical stresses and intensive decomposition of gas hydrates with the release of free methane:

1) The unloading zone (Zone 1 in Figs. 2 and 3) of undermined rock layers and coal seams. The transition of solid coal-gas solutions into the gaseous state in these zones is confirmed by the value of efficiency of gas drainage up to 0.85 when using boreholes drilled into the mined-out space from the earth's surface or underground workings [5].

2) The unloading zone (Zone 2 in Figs. 2 and 3) of rocks in the mined seam bottom. The intensity of the transition of methane from SCGS to the adsorbed state is confirmed in practice by periodic breakthroughs of methane from the mine working bottom that is accompanied by fractures of bottom rocks and increasing methane concentration.

3) Zone of partial horizontal stress drop in the edge sections of the mined seam (Zone 3 in Figs. 2 and 3), as evidenced by coal sloughing on the face, roof fall and increasing methane release. A feature of this zone is the deformation of rock layers and coal seams along their natural contacts and technogenic fractures. Under the influence of tangential and alternating-sign normal stresses in these zones, blocks and oblique fractures are formed along which methane migrates.

4) The zone of vertical stress drop (Zone 4 in Figs. 2 and 3), arising due to the expansion of undermined or bottom coal seams. Since the tensile strength of coal is 10–15 less than its compressive strength, intensive crushing of coal and the transition of methane to free gas state takes place, according to the diagram in Fig. 1.

5) The zone of alternating-sign stresses and deformations arising under the influence of geological dislocations/faults, the boundaries of geotectonic blocks [21].

6) The zone of migration of methane-air mixture between the mined-out spaces of the adjacent extraction pillars. According to Fig. 2, zones of tensile horizontal stresses and great compressive stresses arise above the coal pillars between adjacent extraction districts. Under the influence of alternating-sign stresses and strains, the formation of technogenic fractures occurs, along which the methane-air mixture migrates to the workings of the extraction pillar.

As follows from the diagram in Fig. 1 and the nature of the stress distribution in the rock mass in Figs. 2 and 3, in coal seams outside the zone of influence of mine workings or geological dislocations, one should not expect intense methane release, since all the mechanical stresses are compressive, that is, they reduce the coal porosity and the intensity of methane filtration. This is confirmed in practice in a seam degassing, where the average efficiency of gas drainage is 0.20.

With the aim of increasing the intensity of seam degassing using a borehole system, some authors [3, 7, 11, 12] propose various methods for coal crushing and increasing permeability. At the stage of experimental verification, the following methods for impacting a rock mass are tested: electropulsed, periodic plasma-pulsed, vibration microwave, fluid disruption, vacuum degassing, etc. However, according to the calculations from paper [14], with increasing porosity of coal mass without mechanical stress drop, filling of voids with gas and increasing pressure in the coal matrix occurs. In this case, it is necessary to create a surface to be free of mechanical stresses, through which methane flows into mine workings or boreholes.

According to the graphs in Fig. 4 and research [6] at the first stage after connecting a borehole to the degassing system, the degassing intensity is high, and after a few days it gradually decreases.

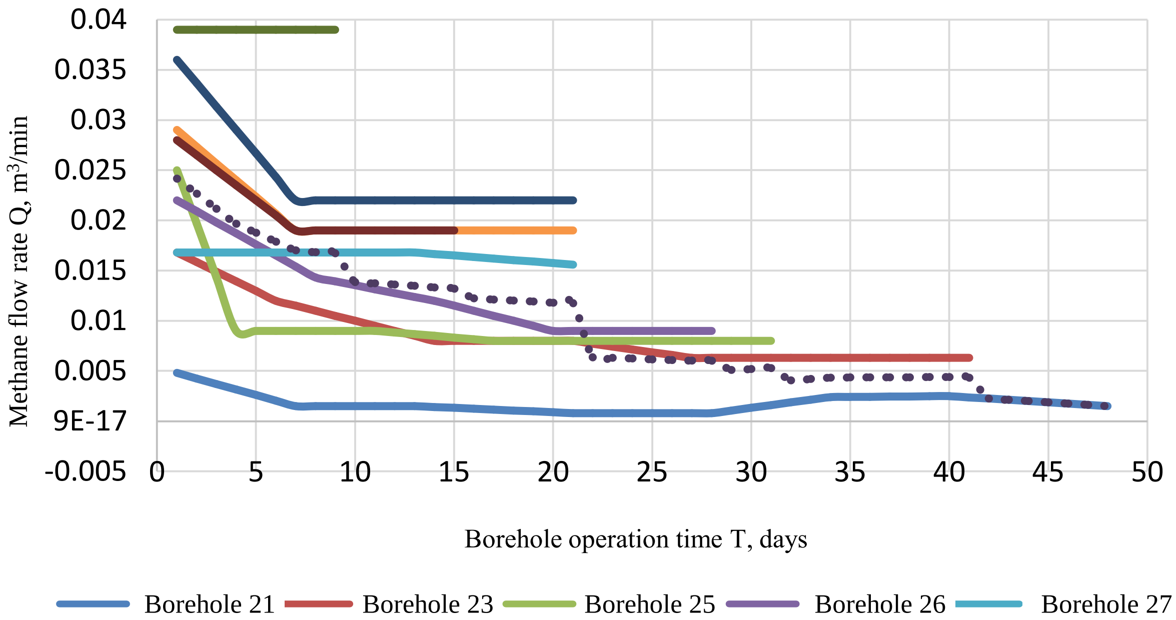

Fig. 4. Plot of methane flow rate from degassing boreholes during seam degassing as function of the borehole operation, seam 16, Abashevskaya mine, Kuzbass

The reasons for the decrease in the borehole methane flow rate are coal crushing with the borehole filling. At the C.M. Kirov Mine, experiments were conducted to enhance degassing in the vicinity of boreholes by means of anthropogenic impact on the boreholes; however, the results do not differ significantly from those shown in Fig. 4.

New technological solutions for methane recovery from coal-rock mass were proposed in a paper of scientists of the Republic of Kazakhstan [17]. The authors argue that the use of several technogenic impacts on rocks through boreholes drilled from the earth's surface does not provide the design flow rate of methane. Of the 150 boreholes in the Karaganda coal basin, only few boreholes produced gas encroachment rate of 3–4 thousand m^3 per day. High labor and energy intensity of the application of seam hydraulic fracturing is noted, at low efficiency of the method. The reasons for decreasing gas recovery factor after the hydraulic fracturing is blocking of methane in the pores and locking of the fractures with swelling clay particles.

Thus, the traditional methods of degassing coal seams, regulated by applicable documents, do not ensure effective degassing of the seams above 0.4.

Therefore, it is proposed to expand scientific research for the development of a new direction in order to create and implement combined methods of phased degassing using methods of reducing mechanical stresses in a coal matrix with preliminary increasing its porosity.

In connection with the above, a research program has been developed including the following types of work:

1) Plasma-pulsed impact on coal seams through boreholes drilled from the earth's surface [22]. The technology is based on the effect of a strong compression wave on rocks, resulting from the intense expansion of a plasma channel formed between special electrodes. As a result of the conductors closing, an explosion occurs, a strong shock wave is formed, compressing and tensioning the environment. Microfractures arise, which are filled with methane.

This method is implemented when performing early degassing in the conditions of the Yerunakovsky Vostochny area of the Yerunakovskaya-VIII Mine in the Kuzbass. Four vertical boreholes were drilled from the surface. The depth of vertical boreholes for the conditions under consideration is up to 700 m. Coal seams 48 and 45 of the Lenin suite ($P2_{ln}$) of medium thickness, with a gas content of about 25 m^3/ t dry ash-free mass. The target scope of drilling is presented in Table 1.

Table 1

Scope of drilling

Borehole	Target depth, m	Borehole purpose	Drilling method	Within extraction district outline
1	580	Degassing	Noncore	48–5
2	550	Degassing	Noncore	48–5
3	600	Degassing	Noncore	48–6
4	630	Degassing	Noncore	48–6

2) Plasma-pulsed impact on coal seams through boreholes drilled from the earth's surface and/or from underground workings. The technology is being developed relating to the possibility of using technical means in underground conditions.

3) Directional drilling of long (up to 1200 m) degassing boreholes for preliminary degassing of coal seams in the outline of extraction pillars planned. The method is implemented at the Kuzbass mines.

4) Drilling of degassing boreholes along a seam dip with the introduction of a polyethylene pipe into the borehole to its entire depth for dewatering the borehole and the gas recovery from the borehole bottom (increasing the gas mixture movement speed occurs).

The implementation of the combined methods of phased degassing using methods of reducing mechanical stresses in a coal matrix with preliminary increasing its porosity allows increasing methane yield up to 90 %.

Conclusions

The analysis of methods and directions of increasing the efficiency of coal seam degassing showed that:

1) The traditional methods and means of degassing, regulated by the applicable specification documents, ensure the achievement of efficiency of gas drainage in the range of 0.03–0.44, no more than 0.28 on average in the Kuzbass; using combined degassing methods with simultaneous gas suction and seam degassing increases this figure up to 0.55; applying boreholes drilled from the earth's surface raises efficiency of gas drainage to 0.85.

2) A promising direction for increasing the efficiency of methane-bearing coal seam degassing is the development of the theory and practice of combined phased crushing of coal matrix in order to create conditions for the transition of methane from hydrate to gaseous state through reducing mechanical stresses in the rock mass.

3) The main directions of increasing the efficiency of coal seam degassing in the coming years shall be: plasma-pulsed impact on coal seams through boreholes drilled from the earth's surface and/or from mine workings; coal seam degassing through long boreholes (up to 1200 m) using polyethylene pipes inserted in them for dewatering the boreholes and the gas recovery from the borehole bottom.

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