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CMM RECOVERY, UTILIZATION AND COGENERATION BY COMPRESSOR PLANTS

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ДОБУВАННЯ, УТИЛІЗАЦІЯ І КОГЕНЕРАЦІЯ ШАХТНОГО МЕТАНУ КОМПРЕСОРНИМИ УСТАНОВКАМИ

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ДОБЫЧА, УТИЛИЗАЦИЯ И КОГЕНЕРАЦИЯ ШАХТНОГО МЕТАНА КОМПРЕССОРНЫМИ УСТАНОВКАМИ

Abstract. The article presents the designed schemes and compressor plants for degassing coal beds and utilizing coal mine methane (CMM) and automatic system for controlling their operation. Interdependence between methane-bearing coal structure, permeability and absorption properties are analyzed. A model of influence of gases, which differ by their sorption energy, on the coal bed and possible schemes for intensifying methane recovery from the coal beds are described. A plant was designed for degassing the underground beds, in which rotary compressor pumps out the gas mixtures and degases the beds without characteristic formation of crystalline hydrate with methane. A station was designed for mine gas utilization. A method is proposed for methane recovery, which assumes pumping of carbon dioxide into the coal bed, which, due to the higher sorption capacity than that of methane, displaces methane adsorbed by the coal. Plants УКГ (Compressor Gas-Utilizing Plant – CGUP) were designed for methane utilization and combustion in special chamber and for preventing methane from escaping into atmosphere, or for feeding it to the equipment for use in energy sector (production of electricity and heat). The experience on using this technology and equipment with the view to increase the coalbed methane (CBM) recovery from the coal beds is presented.

Keywords: compressors, CMM (coal mine methane), recovery, utilization, cogeneration.

Gas contamination of the mine tunnels and emergence of endogenous and exogenous fires in underground roadways and goafs are the main factors which threaten safety of human life and health and require immediate operational analysis and decision making. Large reserves of coal bed methane (CBM) is a good reason for developing new, highly efficient technologies for the CBM recovery [1-3]. In this view, it is a vital need to create a compressor plant which could utilize coal mine methane (CMM) from operating or closed mines, and, consequently, decrease greenhouse gas emissions.

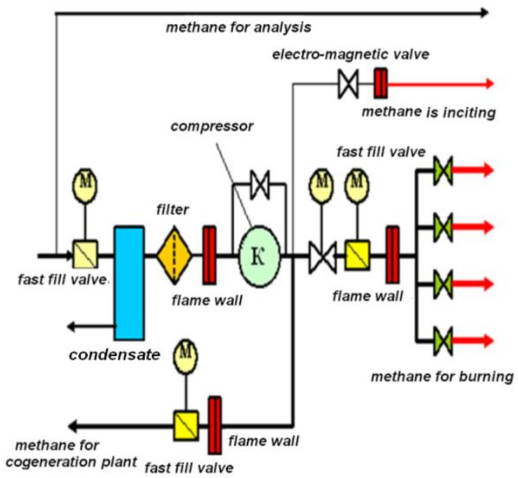

Figure 1 – Scheme of the plant УКГ 5/8 for draining CBM away from the coal seams with its further utilization

Today, a lot of schemes and compressor plants for draining CMM away from the coal beds with its further utilization (Fig. 1) and automatic system for controlling their operation have been designed [4], in which devices for explosion primary protection prevent formation of explosive gas mixtures: in case of their excessive concentrations, the system, which continuously monitors methane concentrations and oxygen presence in the CMM, switches off the plant in order to prevent formation of explosive gas mixtures.

The compressor gas-utilizing plant (CGUP) УКГ-5/8 of container type was designed for utilizing CMM from operating and closed mines by burning it in a special chamber and for preventing the harmful greenhouse gas - methane (CH_4) from escaping into atmosphere. These plants can pump gas directly from the methane drainage boreholes. Explosion protection is ensured by continuous monitoring of methane concentration. When the concentration is 1%, the plant is switched off. The plant is equipped with explosion-proof equipment and flame walls. The УКГ-5/8 technical performance is limited by 8 MW of heat energy and optimal continuous capacity of 5 MW. The plant provides continuous automatic analysis of arriving gas by content of CH_4, CO_2 and O_2 in it. It is well-known that methane is 21 times more harmful than carbon dioxide, which is formed when it burns in the plant.

Interdependence between structure, permeability and absorption properties of the methane-bearing coal was analyzed (Fig. 2). The coal samples are characterized by the developed surface and porous structure with macro-, micro- and nanopores. Such surface absorbs methane well. Peculiarities of the coal structure lie in the fact that it represents a natural polymer material in the amorphous state with a developed porous structure, completely or partially filled with fluids which are also present in intermolecular space of polydisperse self-regulating multi-component mass, which can change its structure under the effect of external stresses and adsorbed gases.

a) b)

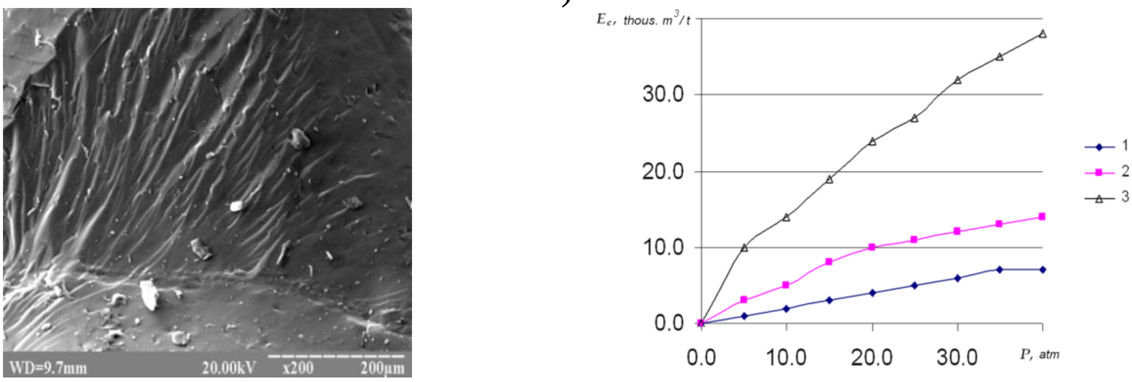

Figure 2 - Structure of coal-surface cleavage (a) and dependence between sorption capacity of different gases (b) and pressure: 1 - nitrogen, 2 - methane 3 - carbon dioxide

Fig. 3 shows a model of impact of gases with different sorption energy on the coal beds and possible schemes for intensifying methane recovery from the coal beds.

a) б)

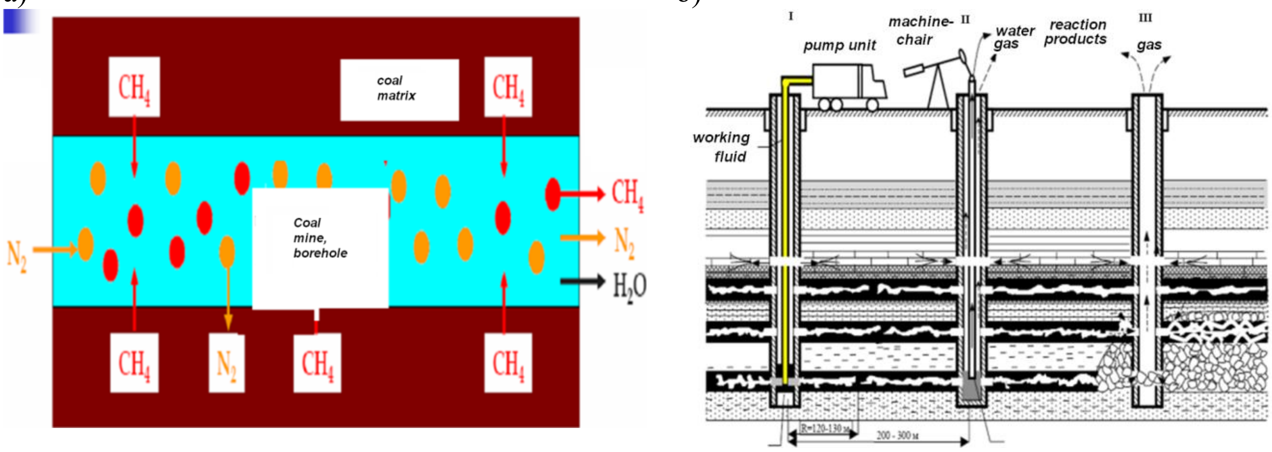

Figure 3 - Model of gas impact on the coal beds (a) and possible scheme for intensifying methane recovery from the coal beds (b) by using membrane nitrogen plants

Plant for draining methane away from the underground beds. Fig. 4 presents the designed plant for draining methane away from the underground beds [5], which operates in the following way. The platforms 12 and 13 are separately delivered to the working area in the mine and are connected by flexible sleeves 14: inlet fitting 1 is connected to the bridging line with the borehole (is not shown), through which the gas is drained away from the bed, and fitting 9 is connected to the line for gas withdrawal (is not shown). When the drive 7 of the rotary compressor 6, which is connected with the return valve 3, suction muffler 4 and suction filter 5, is switched on, the rotary compressor 6 pumps the gas mixture out from the underworked seam and, consequently, degases the seams without traditional formation of crystalline methane which blocks the flow channels in the equipment of conventional plants and, therefore, reduces the equipment life.

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a) b) c)

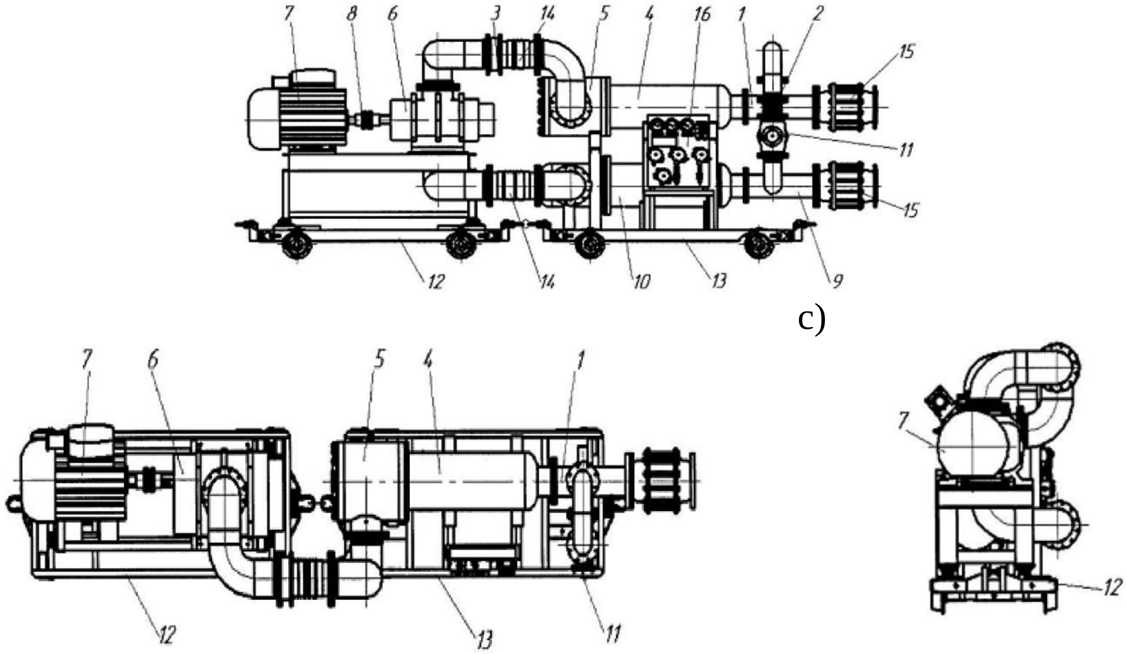

Figure 4 - Plant for gas drainage from the underground beds:
a) front view; b) top view; c) side view

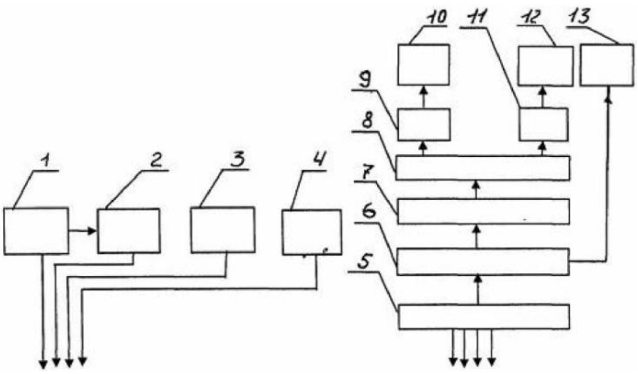

Figure 5 - Technological chain for the methane recovery method

A method for methane recovery.

The method [6] is realized through the following chain of equipment (Fig. 5): discharge pump 1, which creates hydraulic shocks and simultaneously accumulates hydraulic energy flow; accumulator 2, which is used after the hydraulic shock in order to feed, under high pressure, working fluid to the bed; cylinders 3 with carbon dioxide, or unit 5 for producing carbon dioxide, which further is pumped into the coal bed and, due to its higher sorption capacity than that of methane, displaces methane adsorbed by the coal; cylinders 4 with nitrogen or nitrous station (with a device for gas heating, for example, up to temperature 160-170°C for the best absorption of methane) where nitrogen displaces methane, prevents spontaneous combustion of coal and reduces risk of explosive process occurrence while recovering methane; gas-gathering collector 5, which connects the boreholes in area of the coal bed; ejector 6, which increases pressure of low-grade gas for its further displacement; system 7 for cleaning and drying methane mixture to be used as an energy fuel; systems 8 for methane mixture enriching and improving the fuel energy potential; compressors 9, which compress methane in the tanks, feed it to the power plants into the containers 10 used for methane storage; power plants 12 such as, for example, gas-electric generators; and utilization plants 13 such as, for example, methane combustion plants.

Plants УКГ for methane utilization. The plant [7] is developed for mine gas utilization. Fig. 6 illustrates scheme of the block for the mine gas burning and utilization.

The mine gas burning block operates as follows. Mine gas flows from the compressor machine through the pipeline 8, passes the valve, which regulates the gas flow and which is automatically opened when power is supplied to the distribution cabinet in the mine gas burning block, then passes the emergency valve 2, which is required for manual cutting the pipeline off in case of emergency and should be always opened when the block works. Further, the mine gas passes through the device 3 for flame extinguishing, which consists of a set strips made of high-grade stainless steel, and enters the unit 4 for measuring the mine gas pressure and temperature, by indications of which the mine gas flow is adjusted. Then, the mine gas passes the relay unit 5 with two pressure switches (max / min), which monitors the output pressure in the burners. Then the mine gas enters the magnetic system 6, which consists of a set of ring magnets (are not shown) made, for example, of barium ferrite, with residual induction of at least 0.1 T and is installed in the pipeline made of weakly magnetic steel located in the entrance into the distribution pipeline with igniting burner and four main burners 7 (burner holes have, for example, a spiral shape for twisting the combustible gas flow and its more efficient mixing with air in the torch); the ring magnets have alternating location of their poles, and channels for gas-mixture flowing are laid through individual tubes with no direct contact between gas and magnets. Finally, the mine gas enters the combustion chamber 10 consisting of a combustion chamber table 11 and combustion chamber roof 12, which is equipped with an inside protective heat insulation in order to avoid destruction due to high combustion temperature. The combustion chamber is equipped with outflowing gas analyzer 9 and probe 13 in order to control and optimize the combustion process.

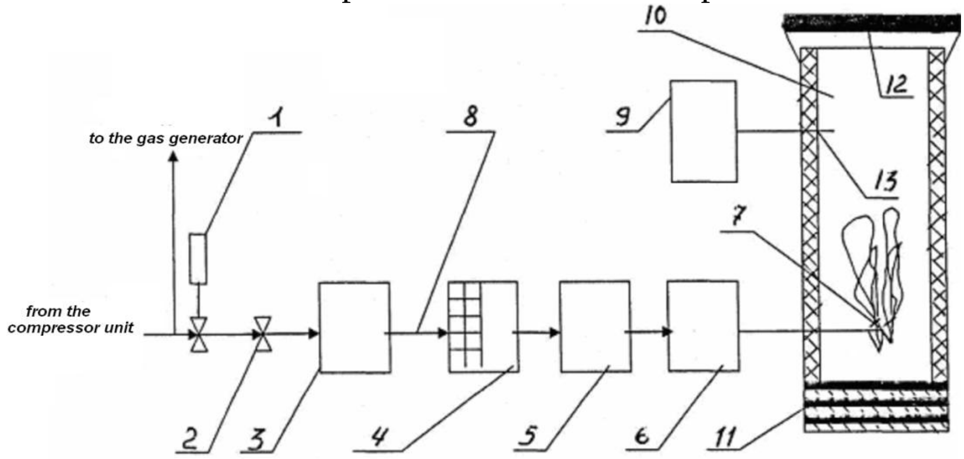

Figure 6 – Mine gas burning block

The main design stages of the compressor gas-utilizing plant УКГ include:

1. To develop Technical Task for the gas-utilizing compressor plant УКГ 5/8, which shall be approved by JSC "Krasnodonvugillya" .
2. To develop a program of and methods for preliminary and acceptance tests.

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3. To obtain from the Donetsk Technical Expert Centre an expert's conclusion on the equipment compliance with requirements of regulations on labor protection and industrial safety.

4. To conduct acceptance tests of the plant prototype at the Komsomolets Donbasu Mine.

5. To develop and approve Technical Specifications.

6. To obtain from the Donetsk Technical Expert Centre an expert's conclusion on the high-risk equipment compliance with requirements of regulations on health protection and industrial safety.

7. To put into operation the compressor gas-utilizing plant УКГ with further its widespread implementation in the Ukrainian mines.

Over the last decade, the NIKMAS Concern has designed and mastered manufacture of the plants for methane utilizing technology, which recover, compress and prepare methane to be used in energetic industry. In 2008, the first lot of Ukrainian gas-utilizing compressor plants УКГ 5/8 was manufactured for the CMM recovery and utilization in operating and closed mines. The УКГ 5/8 is designed for methane combustion in special chamber and for preventing methane from escaping into atmosphere, or for feeding it to the equipment for use in energy sector (production of electricity and heat). The plants were tested and implemented in the Ukrainian mines (Fig. 7).

Figure 7 - The exterior of the gas-utilizing compressor plant УКГ 5/8

The plant equipment is arranged in a 20-foot noisestop isothermal steel container. The container protects the equipment against mechanical damage and environmental influences.

The plant can be transported to the object by road, and its putting it into operation on the coal deposit territory does not require significant capital expenditures.

The plant is equipped with remote monitoring system for remote monitoring the network in the mine.

Special interest presents usage of the technology for purifying gas from the components which do not burn. The NIKMAS Concern is in the process of developing the manufacture of the plants for gas-components separation by advanced membrane technologies. Design of the equipment for the methane enrichment is based on the latest scientific and technological achievements thank to which the equipment features technical characteristics similar to the advanced foreign analogues. The technology for methane denitrification and enrichment on the polymer membranes allows to get gas that meets all exacting requirements for the fuels. The gas-component separation scheme in the process of methane enrichment is shown in Fig. 8.

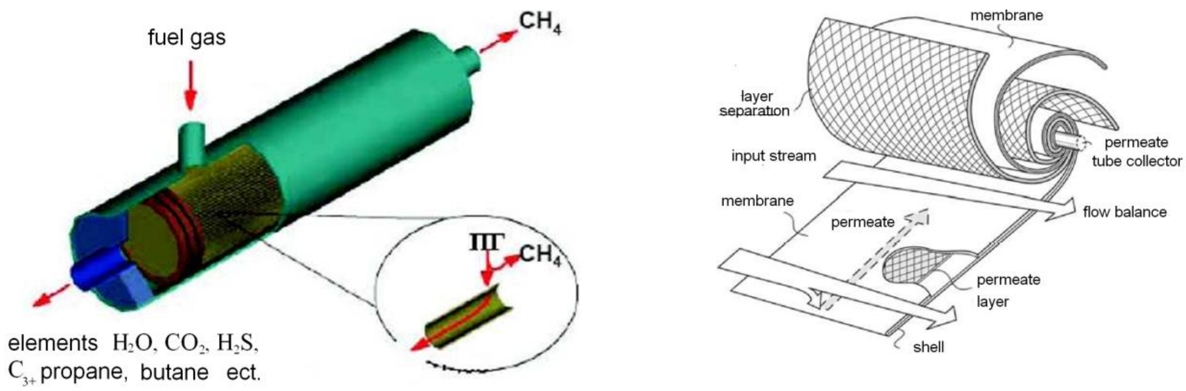

Figure 8 - Scheme of gas-component separation on the membrane unit

Today, the main method for separating nitrogen from methane is cryogenic technology (division into fractions at low temperatures). Recently, a method for gas denitrification (methane enrichment) by separation on the membranes is being actively implemented. As nitrogen and methane molecules are much the same by their size, conventional polymer membranes can not separate them. To solve this problem, membranes were designed with silicone separation layer in which components are separated depending on different rate of absorption (sorption) and not depending on the velocity of nitrogen and methane molecule penetration (diffusion).

The pressured gas flows to the silicone layer, is dissolved here and penetrates to the opposite surface layer, where it re-releases and flows further in gaseous state. Both gases (nitrogen and methane) penetrate through the separation layer very quickly, but they have different rate of dissolution (absorption) in silicone, so this membrane is able to separate them effectively.

Area of membrane surface in each module is from 20 m^2 to 50 m^2. Fig. 9 shows the membrane layer in section. The thinnest layer is the silicone separation layer below which is chemically stable porous base, which does not prevent mass transfer. And the lower layer is polyester, which shall ensure mechanical strength. As an example of such membrane use, let’s consider a scheme of the plant for natural gas denitrification. Block diagram of membrane plant is shown in Fig. 10.

Specification of the plant: gas performance - 50 000 nm^3/day (2083 m^3/hour); gas input pressure - 1.8 MPa; needed nitrogen volume in the exit from the membrane - 10%. In the plant under the consideration, two membrane blocks are used. Gas stream 1 containing about 38 % of nitrogen is mixed with gas stream 2 (permeate from the first membrane block). The permeate (filtrate) is a mixture of gases formed when gas has passed through the membrane. Before the mixing, the stream 2 is compressed by the compressor 1 to the working pressure of 1.8 MPa. The stream 3, which is a mixture of streams 1, 2, 20 (retentat is a stream, which fails to pass through the membrane), flows to the first membrane block. This stream contains already 35.3 % of nitrogen and 62 % of methane. The stream 3 is divided in the membrane block into the stream 2 (retentat returns to the first membrane block), stream 15 (retentat containing > 78% of nitrogen is regarded as unsuitable gas and is removed away from the system) and stream 7 (which is one of the components, which is used in the second membrane block). The stream 7 and stream 16 (permeate from the second membrane

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block) are again compressed from the pressure 0.17 MPa up to 1.93 MPa with the help of the compressor 2. The resulting gas stream 12 contains >76% of methane and <19% of nitrogen. As a result, three gas flows are formed on the second separation membrane block: stream 16, which returns to the second membrane block; stream 20, which returns to the first membrane block; and stream 18 is consumer gas, which is produced by the plant and which contains >82% of hydrocarbons and <10% nitrogen.

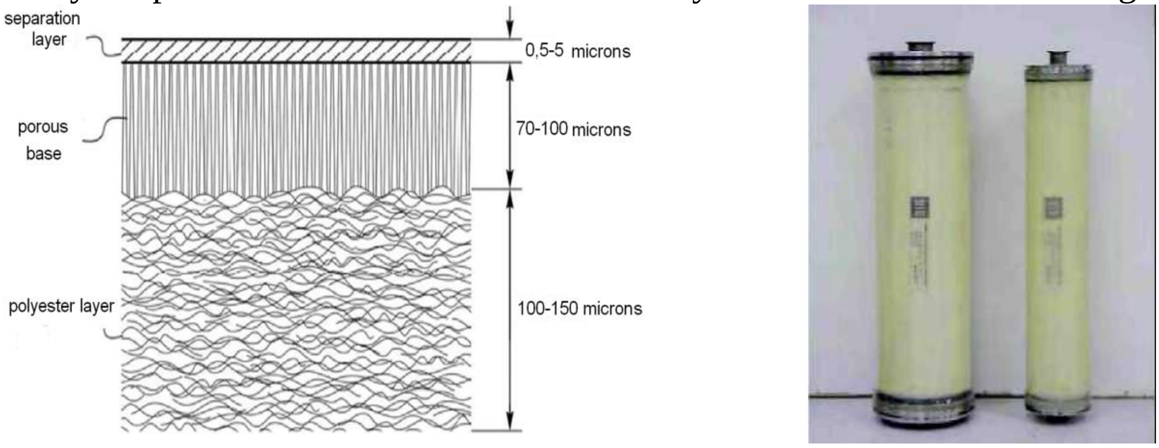

Figure 9 – Block diagram of the membrane and general view of the membrane modules

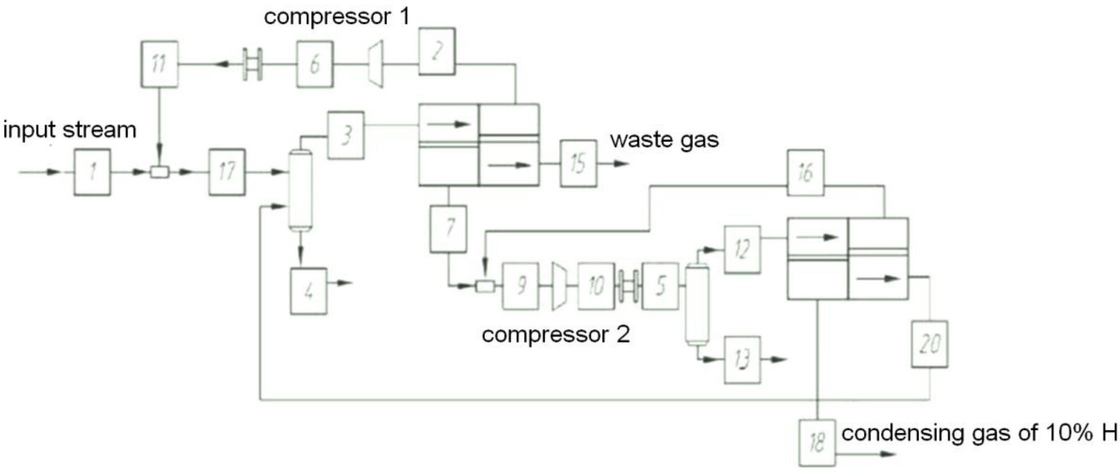

Figure 10 - Block diagram of the membrane block

Figure 11 - Methane enrichment membrane module

Table. 1 demonstrates a detailed balance of derived gas flows with operating temperature, pressure, consumption and volume content of the components: nitrogen, methane, ethane and others.

Fig. 11 shows an example of membrane module of denitrification arranged on the common frame. Capital expenditures for the plant, which include cost of the compressor plant, membrane modules, drying systems and gas cleaning, can be compensated within 2.3 - 3 years in average. The membrane separation systems can be used in different spheres, including gas-fuel preparation for generators and motors; separation of accompanying gas; denitrification of gases; cleaning gas from CO_2 and H_2S .

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Table 1 - Characteristics of gas streams

Stream No.	1	3	2	15	9	12	16	20	18
Operation	Supply	Input membrane	Absorption compressor		Absorption compressor	Input membrane II	Return	Return	Product
Mass flow, kg per hour	2018,68	6740,87	3711,38	971,061	2415,11	2415,11	356,681	1011,03	1047,36
Temperature, ° C	25,0000	40,8304	34,3200	30,4951	40,1002	48,8889	43,4361	42,3242	46,7187
Pressure, kgf / cm^2	18,3549	18,3549	1,758	17,4409	17,58	19,686	1,758	19,334	1,758
Mole fraction of steam	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Rate of heating (15 ° C)									
Total kJ (kg mol)	5,927 E+005	5,955 E+005	5,894 E+005	1,909 E+005	7,604 E+005	7,604 E+005	8,008 E+005	6,238 E+005	8,7I8 E+005
Working kJ (kg mol)	5,350 E+005	5,368 E+005	5,31 E+005	1,7I9 E+005	6,859 E+005	6,859 E+005	7,222 E+005	5,620 E+005	7,874 E+005
Volumetric stream, m^3 / day	3010,3447	111,172061	64202,3789	1346,2489	45042,5391	4059,5610	7027,4233	1650,8524	20229,9883
Liquid, m^3 / hour	4,4376	154,163	8,549	1,4762	6,3872	6,3872	1,0021	2,4258	2,9593
Steam, m^3 / day	49999,996	174338,81	97191,585	20517,49	66967,750	66967,75	10338,17	27163,77	29465,810
Components,%									
Methane	57,441002	62,398046	63,507915	21,35917	76,427758	76,42776	82,27282	67,61168	82,504302
Dimethyl	2,156000	1,273435	0,913640	0,032968	2,355045	2,355045	2,435469	0,936469	3,634576
Propane	1,045000	0,488764	0,273830	0,002850	1,009876	1,009876	0,879392	0,233890	1,771017
N-Butane	0,259000	0,097362	0,036212	0,000059	0,219474	0,219474	0,120381	0,018596	0,439425
1-butane	0,225000	0,084581	0,031459	0,000052	0,190663	0,190663	0,104578	0,016155	0,381740
N-pentane	0,061000	0,021578	0,007009	0,000006	0,050403	0,050403	0,023456	0,003061	0,103501
1-pentane	0,082000	0,029936	0,010179	0,000011	0,068440	0,068440	0,034221	0,004783	0,139130
Neopentane	0,003000	0,001095	0,000372	0,000000	0,002504	0,002504	0,001252	0,000175	0,005090
N-Hexane	0,116000	0,040363	0,011493	0,000006	0,094334	0,094334	0,038461	0,004419	0,196827
Nitrogen	38,040000	35,253853	34,997559	78,59614	18,995459	18,99546	13,53832	30,98195	9,860071
Carbon dioxide	0,562000	0,300012	0,199531	0,005313	0,572762	0,572762	0,537301	0,177309	0,949763
Oxygen	0,010000	0,010680	0,010802	0,003443	0,013284	0,013284	0,014344	0,011503	0,014555

The technology and equipment used for increasing methane recovery from the coal beds. Ensuring of energy efficiency and improvement of competitiveness of commodities produced by mining enterprises with simultaneous reduce of anthropogenic impact on the environment are the most important challenges. It is well-known that the CBM world reserves exceed reserves of natural gas and are estimated at the range of 260 trillion m^3. Share of Ukraine accounts for about 12-25 trillion m^3 [8].

In the CBM production, leadership belongs to the USA, which in 1980th began to drill boreholes into the coal beds in the "San Juan" and "Black" basins. In the next decade, Canada is going to implement 10 projects, which assume exploitation of gas deposits in the coal beds of British Columbia. In the USA, coalbed gas is considered an unconventional source of natural gas, though in China the situation is opposite: here, the largest five gas fields are comparable with coal deposit resources in the western part of China: proven reserves are 67.8% of the total gas resources of the country. It should be noted that during the last years, coefficient of methane recovery from the coal deposits by methane-draining methods does not exceed 0.25. Volume of methane output essentially depends on the applied method of recovery.

It is believed that the most effective way to reduce methane escaping into the mine tunnels is methane drainage from the coal bed and collecting the natural free-gas accumulations through the boreholes drilled from the earth's surface or from the underground tunnels. Technical characteristics of the common methods for intensifying methane recovery from the coal beds are presented in Table. 2.

Table 2 - Common traditional methods for intensification of methane recovery from the coal beds

Methods of intensification	Conditions of applicability	Frequency of use
Hydraulic fracturing of the coal beds	In different geological conditions	> 85%
Cavitation (air-hydrodynamic effect)	Coal beds with total thickness of more than 20 m with interval of occurrence up to 100 m, with permeability more than 30 mD. Seam pressure is higher than hydrostatic pressure	< 10%
Extending of the open bottom hole	Coal beds with high rate of penetration and with permeability of 100 mD and more	< 5%
Directional and horizontal drilling	Coal beds with low rate of penetration and with thickness of > 2 meters	1%

It is obvious that knowledge of CBM and dynamic and gas-dynamic phenomena require further clarification. Some scientists state that the coal seams bedded below floor of zone with gas weathering are impermeable for filtering mode. It should be mentioned that methane in the coal beds is presented in various forms: 10% - in the free state, that is natural gas state, and 90% - in the state associated with coal adsorbed by surface of coal, cracks or pores, or as a solid solution.

Coal can be present as a polydisperse self-regulating multi-component formation, which is able to change its structure under the effect of external stresses and adsorbed gases, and which is a kind of natural macromolecular polymer with developed porosity and with molecules of methane and other gases adsorbed by the surface of and dissolved in the intermolecular space. At the same time, it should be taken into account that methane can be dissolved in water. For example, water from depth of 700 m can contain dissolved methane in volume 1.5 times greater than volume of the water itself. Molecular structure of the coal is shown in Fig. 12.

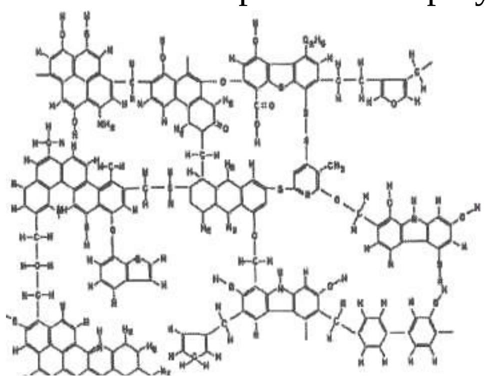

Figure 12 - One of possible structures of carbon molecules

A model of the coal blocks building and coal fractured structure are shown in Fig. 13.

The proposed technology is based on the use of binary gas, including CO_2 and nitrogen, pumped into the coal beds in certain amounts, proportions, sequence, given

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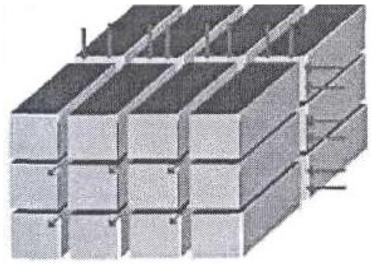
values of pressure, exposure time, and with further use of the pumped-out gases. Physical factor of the proposed technology efficiency lies on the coal energy sorption which differs for different gases. It should be mentioned that injection of CO_2 can cause swelling of the coal. But this problem can be overcome by standard methods, such as a hydraulic fracturing.

a)



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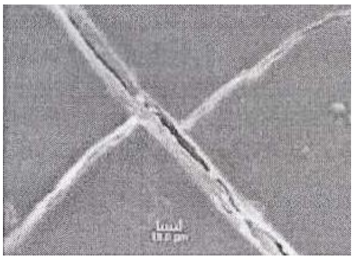

Figure 13 – The known model of coal blocks building and gas flowing in it (a); coal fractured structure (b)

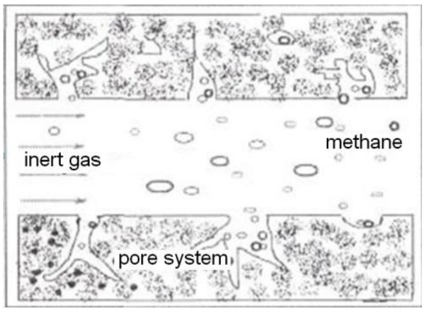

Figure 14 – Model of methane displacement by nitrogen

The United States of America, Great Britain, Germany, China, Canada, Australia, Japan and other countries show great interest to these technologies. One of the reasons why the field projects have not become profit-proved yet is relatively high cost of CO. Therefore, as a variant, it is proposed to use CO_2 from the power plants. Some other details about using of the new method are presented in Table. 3.

A model of methane displacement by nitrogen is shown in Fig. 14. Pumping of nitrogen reduces partial pressure of methane in the free space (in the borehole or mine), and methane is released from the porous coal. Energy of CO_2 molecule sorption by coal is higher than sorption of CH_4 molecules, therefore, with the lapse of time, CO_2 is adsorbed by surface of coal, while methane is desorbed, released into the free space and flows with the stream of nitrogen.

Pumping of gases displaces methane, forcing it moving in the blocks, cracks and porous media, and causes diffusion of the coal. Methane molecules are adsorbed by the coal surface, on which a layer of water can be present. The molecules can be desorbed due to heating, pressure reducing, adding of other gases with higher energy sorption into the gas environment. Pressure changed after the gas pumping provokes occurrence of diffusion flow. Density of diffusion flow can be expressed by the known ratio:

$$J = -D\left(\frac{dc}{dx}\right),$$

where D is diffusion coefficient; $\frac{dc}{dx}$ is concentration gradient.

Table 3 - Information about the technology of increasing methane recovery by way of pumping CO_2 and nitrogen

Characteristics of publication	Country	Source
Development of partnership project between Japan and Australia on use of CO pumping with the aim to increase the methane recovery from the coal beds	Japan, Australia	Project. CFE-06-13: CO_2 Enhanced Coal Bed Methane (CSIRO-JCOAL-ECBM)
The project of pumping greenhouse gas CO_2 into deep coal beds and simultaneous increase the methane recovery	Canada	Shannon D. Phelps and all.//Coal bed methane ownership and responsibility: a summary of surface, mineral, and split-estate rights
Project on utilization of C_2 from thermal power plants operating on coal (cost - 1.3 million dollars).	USA	-
Project on using Canadian technology with the aim to increase methane recovery by way of pumping CO_2 and nitrogen	China	Project No. A-030841. Development of china's coalbed methane technology/ CO_2 sequestration project
Economic and technical aspects of pumping CO_2 examined in the pilot project in San Juan basin (USA) as an example	USA	Economics of using enhanced recovery of coalbed methane for carbon management.//Coal-Seq 11 Forum. Washington -2003.
Information about the US program on use of technologies that reduce methane emissions by 20 times	USA	http://www.adv-res.com/Research. asp#Outreach
Feasibility of CO_2 pumping in order to increase methane recovery	USA	Topical report January 1, 2004-march 31, 2004 //U.S. Department of Energy. DE-FC26-00NT40924.
Computer simulation of pumping of CO_2 and nitrogen into the coal beds	USA	Wo, Shaochangl University of Wyoming, Laramie, WY . //Simulation of N2/CO_a Injection in Coal Beds: Lessons Learned from Tiffany Field Case Study .
Computer simulation of pumping of CO_2 and nitrogen into the coal beds in Poland. The conclusion was made that it is needed to pump 10^4 tons per 1 year. The results can be expected in 18 months after pumping of CO_2	USA	U.S. Department of Energy. Award Number DE-FC26-O0NT40924.
Modeling of enhanced methane recovery by pumping of nitrogen and CO_2	Canada	New development on coalbed methane simulators for enhanced coalbed methane recovery and CO2 storage. //2002 Denver Annual Meeting (October 27-30, 2002)
Economic analysis and modeling of CO_2 pumping and increase of methane recovery. After CO_2 is injected volume of coal bed is increased.	USA	The Allison Unit CO;,-ECBM Pilot – A Reservoir and Economic Analysis. // International coal bed methane symposium, 2005.
It is shown that the gas desorption changes the coal permeability and porosity . The change of permeability associated with matrix shrinkage is linearly proportional to the volumetric stress or volume of desorbed gas	USA	Influence of gas production induced volumetric strain on permeability of coal. // Geotechnical and Geological Engineering. Volume 15, Number 4 / December, 1997, p. 303–325.

It should be noted that diffusion coefficient of coals has considerable variation, and depends on the size of diffusing molecules, their specific interaction with fragments of macromolecules, mobility of polymer chains, free volume and heterogeneity of the coal structure.

Space-time distribution of concentrations is:

$$\frac{dc}{dx} = \frac{d}{dx}\left(-J\right) = \frac{d}{x} D \frac{dc}{dx}.$$

The three-dimensional diffusion $[c[x, y, z, t]]$ is described by equations:

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$$J = -D\, grad\, c;$$

$$\frac{dc}{dx} = \frac{d}{dx}\left(D\frac{dc}{dx}\right) + \frac{d}{dy}\left(D\frac{dc}{dy}\right) + \frac{d}{dz}\left(D\frac{dc}{dz}\right).$$

Let's consider gas transfer through the coal through-pores. At relatively low pressures or small gas-pore size (r_0) when frequency of collisions of gas molecules with the pore walls far exceeds the frequency of mutual collisions of the molecules, i.e. when average length of the molecule free path is $1 >> r_0$, a so-called Knudsen diffusion can be observed. The gas flow is proportional to the average molecule velocity, and permeability constant is determined by the equation:

$$\Pi = \frac{8 r_0 N_z \pi}{3 N_A} (2\pi mkT)^{-1/2},$$

where Π is surface density of the pores in the coal.

Since average molecule velocity is inversely proportional to the square root of the molecule masses ($\Pi = 1/\sqrt{m}$), components of the divided gas mixture penetrate the pores at different speeds; as a result, the mixture, which has passed through the membrane, is enriched by the lighter components. With increased gas pressure in such porous systems, surface concentration of molecules adsorbed by the pore walls also increases. The formed adsorption layer can be mobile and moves along the surface of the pores, therefore, a surface diffusion of gas can occur in parallel with volumetric diffusion transfer.

Let's consider the most common models (Fig. 15) and equations of adsorption isotherms.

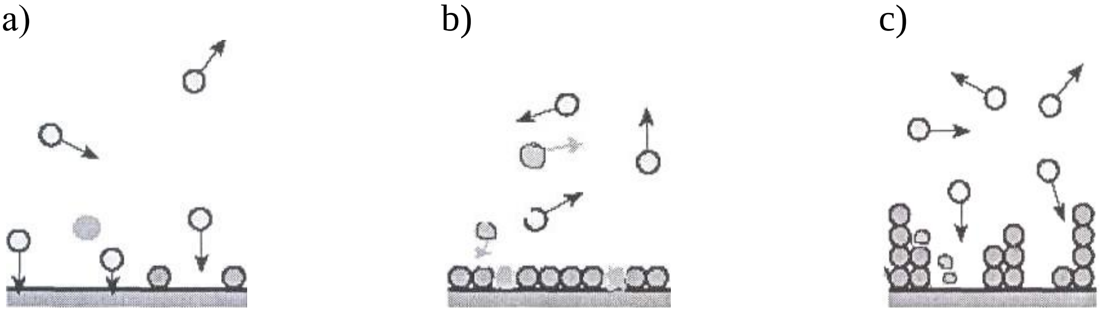

Figure 15 - Model for representation of molecule distribution on the surface of coal, a - model interpreted by the Henry equation ; b – the Langmuir model; c – the BET model

The Langmuir model. According to the Langmuir model, basic provisions for building an adsorption isotherm, are as follows: surface of the adsorbent is homogeneous, i.e. heat of adsorption is the same on different parts of the surface; heat of adsorption does not depend on the presence of other adsorbed molecules, therefore, interaction of adsorbed molecules with each other can be ignored; the molecules can not be adsorbed by molecules of the first layer, and maximal adsorption occurs at the

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hogh-density packing of molecules adsorbed by the surface of the layer with thickness of one molecule. The adsorbed molecules are in the state of dynamic equilibrium with molecules of the gaseous phase. This model leads to the known Langmuir isotherm equation:

$$a = a_m \frac{Kp}{1 = Kp},$$

where K is constant adsorption equilibrium; a_m is maximal adsorption.

In the low pressure equation, the Langmuir isotherm transfers to the Henry equation:

$$a = K_Г p, \text{ where } K_Г = Ka_m.$$

The BET model. The known Brunauer, Emmett and Teller (BET) molecular adsorption theory is based on the model of adsorption process proposed by Langmuir. The BET model takes into account possible polymolecular adsorption.

It is assumed that in order to implement the proposed technology, the mobile nitrogen-membrane compressor stations and gas-utilizing compressor plants of container type designed by the NIKMAS Concern can be used. Drive of the compressor station with capacity of 1000 nm^3/hour receives power from electric motor with capacity 315 kW. The advantages of membrane process used for nitrogen production are explained by low costs and greater resource of the gas-separation membrane stations.

The designed gas-utilizing compressor plant УКГ was integrated into the complex of equipment for methane recovery from the coal beds in the Molodogvardeiskaya Mine. Parameters of the plant are shown in Table. 4. The gas-utilizing compressor plant УКГ of container type (Fig. 16) is designed for the CMM utilization by way of its burning and, consequently, for preventing emission of the harmful greenhouse gas – methane - into atmosphere.

Table 4 - Specification of the gas-utilizing compressor plant УКГ of container type

Operating environment	Mine gas (CH_4 is 25% or more)
Productivity, m^3/hour	570–1551
Differential pressure, kgf / cm^2, not higher	0,1
Rated power consumption, kW	60
Supply voltage, V, not higher	400
Thermal nominal power, mW, not less	5
Gas combustion temperature, not higher than ^{0}C	1200
Dimensions of container, mm, not more length - width - height	6000-2650-2750
The weight of the container with equipment, kg, not more	11 000
Dimensions of pipe, mm, not more - diameter - height	2100–5400
Pipe weight kg, not more	2000

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The known findings of foreign authors, which illustrate effectiveness of the method are presented in Fig. 17. The occurred diffusion processes are accompanied by substitution of methane by molecules of the pumped-in gases, and, thereby, increase methane recovery during its drainage from the coal beds.

Figure 16 – The gas-utilizing compressor plant of container type

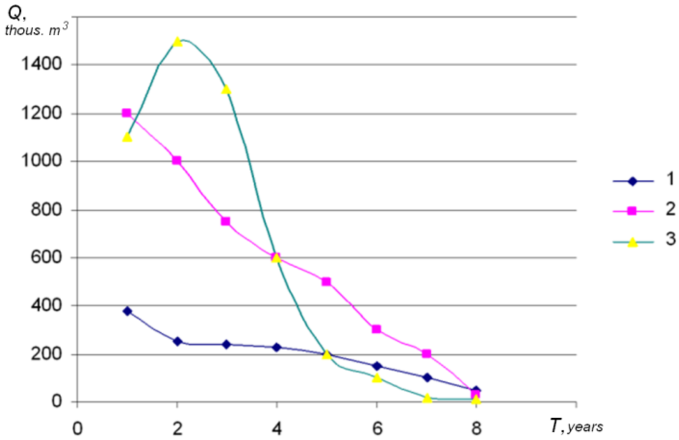

Figure 17 - Dependence of coalbed methane recovery on the time period following the gas pumping: 1 - without pumping; 2 - pumping of nitrogen; 3 - pumping of CO_2

Economic feasibility of the large-scale industrial recovery of methane from the coal deposits was confirmed by successful progress of the coal and gas industries in the USA and obtained results of mining operations in Australia, China and other countries. For example, basing on the USA Department of Energy orders, scientific and research projects (2004) began to use nitrogen to increase methane recovery from the coal beds. Besides, feasibility of using binary gases, one of which was nitrogen, was studied. The Petromin Resources Corporation and the China United Coalbed Methane Co planned to conduct a five-year study of CO_2 injection used for increasing coalbed methane recovery.

Successful solution of these problems increases coal production and reduces its cost, as well as improves completeness and comprehensiveness of power-plant fuel use, safety of the coal underground mining in conditions of growing natural content of methane in the coal beds, and improves environment by limiting methane emissions [9]. The proposed design of compressor machinery and equipment contributes to the implementation of combined technical, technological and economic approach to the improvement of mining industry efficiency.

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Анотація. Розроблено схеми і установки для дегазації вугільних пластів та утилізації шахтного метану, а також системи автоматичного керування їх роботою. Проаналізовано взаємозв'язок структури, проникності та сорбційні властивості вугілля, що вміщають метан. Запропоновано модель впливу на вугільні пласти газів, що різняться енергією сорбції, і можливі схеми інтенсифікації метановіддачі вугільних пластів. Розроблено установку для дегазації підземних пластів, в якій роторний компресор забезпечує відкачування суміші газів, унаслідок чого забезпечується дегазація пластів без традиційних для цього процесу явищ утворення кристалогідратів з метаном. Розроблено станцію для утилізації шахтного газу. Запропоновано спосіб видобутку метану, в якому реалізується накачування у вугільний пласт вуглекислого газу, що унаслідок більшої сорбційної здатності, чим у метані, витісняє адсорбований вугіллям метан. Розроблено установки для утилізації метану УКГ, що призначені для спалювання його в спеціальній камері, запобігання цим виділення в атмосферу або його подачі на устаткування для енергетичного застосування (одержання електрики і тепла). Викладено досвід застосування технологій і устаткування для підвищення метановіддачі вугільних пластів.

Ключові слова: компресорні установки, шахтний метан, добування, утилізація, когенерація.

Аннотация. Разработаны схемы и установки для дегазации угольных пластов и утилизации шахтного метана, а также системы автоматического управления их работой. Проанализирована взаимосвязь структуры, проницаемости и сорбционные свойства угля, вмещающие метан. Предложена модель влияния на угольные пластов газов, которые различаются энергией сорбции, и возможные схемы интенсификации метаноотдачи угольных пластов. Разработана установка для дегазации подземных пластов, в которой роторный компрессор обеспечивает откачивание смеси газов, вследствие чего обеспечивается дегазация пластов без традиционных для этого процесса явлений образования кристалогидратов с метаном. Разработана станция для утилизации шахтного газа. Предложен способ добычи метана, в котором реализуется закачка в угольный пласта углекислого газа, который вследствие большей сорбционной способности, чем в метане, вытесняет адсорбированный углем метан. Разработаны установки для утилизации метана УКГ, предназначенные для сжигания его в специальной камере, предотвращения его выделения в атмосферу или его подачи на оборудование для энергетического применения (получение электричества и тепла). Изложен опыт применения технологий и оборудования для повышения метаноотдачи угольных пластов.

Ключевые слова: компрессорные установки, шахтный метан, добыча, утилизация, когенерация.

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