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## Gas content of the D<sub>6</sub> coal seam

The article deals with the issues of gas content of the most thick and stable D<sub>6</sub> coal seam in the Tentek region. This complex structure seam is dangerous in underground mining for gas and dust outbursts, it consists of coal packs separated by interlayers of mudstones, while the lower layer 0.5-1.5 m thick is very soft, has a strong shear disturbance and is most saturated with methane. Extraction of coalbed methane is a necessary process to ensure the safety of mining operations, to reduce its emissions into the atmosphere, and to utilize it as a fuel and a product for obtaining synthetic materials. The regularity of changes in the particle size distribution of the upper thick pack and the lower thin pack indicates the difference in small coal particles in them, while there are much more of them in the lower layer therefore, the specific surface is larger, which is an important factor of the adsorption processes intensity in the accumulation of methane, and during the gas drainage from the seam. The activation energy of methane from carbohydrate has been determined. A quadratic relationship between methane gas evolution and its initial concentration has been shown. In carbohydrate, it depends on the energy of external forces. A complex relationship has been established between the gas pressure in the coal seam and its concentration and characteristics of the «coal-methane-natural moisture» system. Regularities of changing the methane content of the coal seam depending on its fracturing formed due to the effect of the energy of destruction and the energy appearing with increasing the area of a crack in the coal, have been obtained. The effect of the coal mineral composition on the gas content has been shown.

*Keywords:* methane, particle size distribution, fracturing, drainage, well, energy of destruction.

### Introduction

In the mixture of greenhouse gases, methane can remain in the atmosphere within 9 to 15 years. It retains 20 times more heat than carbon dioxide. Understanding the problem of the presence and interaction of methane with the environment increases the need to develop projects for its extraction from coal seams. Methane processing and utilization has advantages over direct emission into the atmosphere. Possible options of utilizing coalbed methane include power generation, production of compressed or liquefied gas, use in blast furnaces and for calcining lime at the metallurgical plant of the ArcelorMittal Temirtau JSC.

Extraction of methane from coal seams will provide the following benefits: improving the safety in coal mines and the health of miners, selling natural gas and its products, using carbon GNG credits for sale, and increasing coal production [1].

The gas concentration and pressure, the permeability coefficient, particle size distribution of coals are the main factors, which studying makes it possible to estimate the drainage parameters, as well as to calculate the gas balance during coal mining.

The D<sub>6</sub> seam consists of two seams. The upper layer 4.82 - 6.48 m thick is represented by brilliant coal with strong cleavage. The lower one varies in thickness from 0.5 to 1.5 m, has a strong strike-slip fault, and is very soft. The gas pressure in coal is at least 4.5 MPa with its content from 18 to 19 m<sup>3</sup>/t. Based on this, the lower layer is highly hazardous in terms of emissions without the use of drainage. Its initial permeability is less than 0.1 md, and it can increase depending on the natural variability or the man-made impact.

### Results and discussion

Studying the particle size distribution of coals shows that in samples from the upper and lower layers of the seam, 66% of particles are smaller than 0.6 mm, the sample from the lower layer consists of 48% of particles that are smaller than 0.1 mm, while coal from the upper layer consists of only 14% of particles smaller than 0.1 mm (Figure 1) [1].

The larger particles of the upper layer of the D<sub>6</sub> seam are mainly disk-shaped, while the smaller particles are like cubes. The ratio of the shortest to the longest side is on average 3:1 for all sieve hole diameters. The breeze is approximately disk-shaped and 43% of the sample mass consists of “small” particles [1].

The particles of the lower layer of the D<sub>6</sub> seam are mainly rounded. The ratio between the shortest and the longest sides is in the range from 2:1 to 3:1. The particles are similar in shape to cubes and 66% of the sample mass consists of «small» particles.

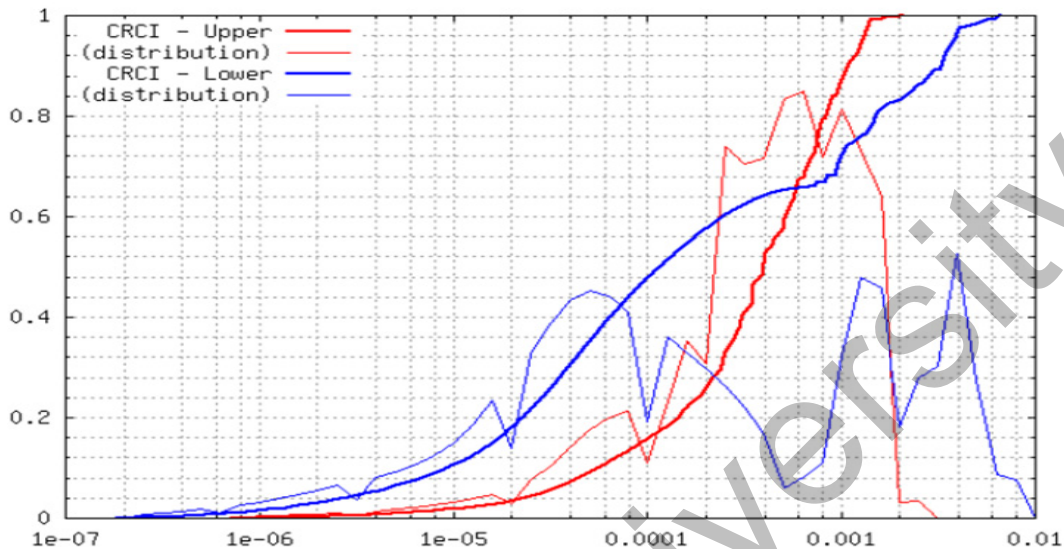


Figure 1. Particle size distribution: the upper and the lower layers of the D<sub>6</sub> seam [1]

To estimate the effect of permeability on drainage, a number of model studies have been carried out for a homogeneous coal seam with the thickness of 6 m and the initial pressure of 4.5 MPa, draining to a gauge pressure of 0.5 MPa. The results are shown in Figure 2, where the abscissa represents the distance between the wells, and the ordinate represents the time required to drain the gas to the pressure of 0.5 MPa [1].

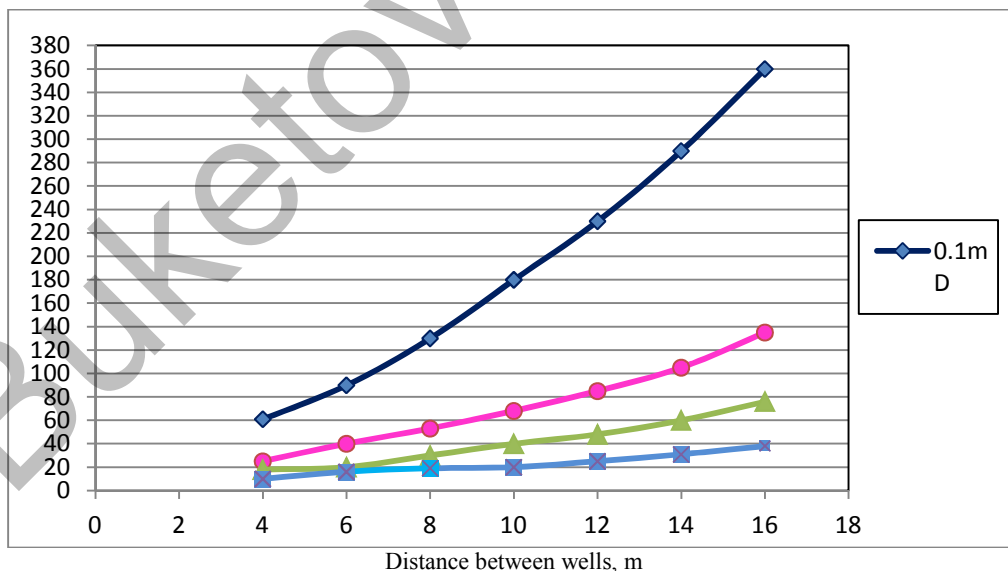


Figure 2. Methane drainage time in the coal seam before reaching pressure of 0.5 MPa depending on the seam permeability and the distance between the wells [1]

Gas permeability of coals is mainly determined by the permeability of endogenous and exogenous cracks, porosity. It inversely depends on the value of the external load and the degree of coal metamorphism, as well as on its gas content and on the degree of filling the filtering volume of pores and microcracks with natural moisture (phase permeability of coal). The amount of methane per unit of dry ash-free coal mass is

determined by the sorption isotherm, and regularly changes with the degree of metamorphism reaching maximum values for natural coals at the semi-anthrocyte stage of 43-45 m<sup>3</sup>/t. Metamorphism processes lead to the transformation of coals, they affect inter-atomic interactions, the essence of which is to simplify their chemical composition and structure carbon in the organic mass of coal [2].

*Methane in coal.* Changing the geomechanical state of coal seams and coal-bearing rocks leads to deformation of interatomic bonds, initiation of chains of relaxation processes in the form of mechanochemical transformation of the organic mass of coal with the formation of gaseous products, mainly methane. The natural methane content of the D<sub>6</sub> coal seam (m<sup>3</sup>/t) at various depths varies too. In the interval of the depth of the upper boundary of methane gases from 180-250 m to the depth of 300 m, the methane content varies within 3-18 m<sup>3</sup>/t; in the depth intervals 301-600 m within 18-28 m<sup>3</sup>/t, and 601-900 m within 30-32 m<sup>3</sup>/t. The forecasted values of natural methane content at the depths from 900 to 1500 m range from 23 to 36 m<sup>3</sup>/t. In works [3, 4] one of the options of the methane state in coals (as a percentage of the total amount) is considered as:

- free: inside macropores, microcracks and other defects of continuity in coals in natural conditions — 2-12%;
- adsorbed: on the carbon surfaces of natural pores and defects of continuity, interblock spaces (including the volumetric filling of transition pores and macroscopic defects-cracks) — 8-16%;
- solid coal-methane solution in the intermolecular space of the substance — 70-80%;
- chemical sorbed methane — 1-2% in defects in aromatic layers of crystallites;
- solid interstitial solution inside gas hydrates solid crystalline substances with the size of 0.38-0.92 nm, that form all hydrophobic gases including methane.

Methane adsorbed by coal is distributed between the solid solution (absorption) and the surface of cracks and pores (adsorption), and since coal has a large specific surface, about 20 m<sup>2</sup>/cm<sup>3</sup>, the amount of adsorbed methane can be comparable to the amount absorbed [2]. This is possible if the binding energy of the methane molecule with the coal surface E<sub>B</sub> is much lower than the energy of the methane molecule entering the solid solution (E<sub>B</sub> ≥ 200 kJ/mol) [4]. If the energy supplied is greater than the energy of the entry of the methane molecule into the solid solution, then the methane molecules begin to leave the coal particle. In this case, the mass of the coal methane particle begins to decrease, similar to the dissolution (melting) of the particle, and this process proceeds according to the law of phase transitions of the first kind. The bond of the methane molecule with the coal substance is mainly provided by the van der Waals forces.

Let's suppose that near the surface of a coal particle, the concentration of methane is C<sub>0</sub>; by supplying external energy (changing the stress state of the coal mass), methane begins to be released from it, the concentration of which near the boundary is C<sub>1</sub>, and at a considerable distance from it is C<sub>∞</sub>.

Using these characteristics, we have obtained the parameter λ equal to [3]:

The dependence of the pairwise decomposition of a coal-methane particle (τ<sub>0</sub>) is determined by the expression τ<sub>0</sub> = λ<sup>-1</sup>. It should be noted that the «apparent» changing of the radius of the coal-methane particle corresponds to changing its mass similar to the dissolution or melting of the coal-methane particle, in proportion to the methane emission from the solid solution. Since the parameter (λ) is proportional to the pressure Δp at the phase interface, the comparison of the obtained regularities of the coal methane decomposition with the isobar of methane sorption at 1 atm. given for the coals of the Donetsk, Karaganda and Kuznetsk basins [4, 5], indicates their coincidence, since the process sorption and desorption are reversible.

When considering the changing of the coal-methane particle radius, it should be borne in mind that small-sized particles are characterized by the decreased surface tension, which leads to decreasing the «melting» temperature of coal-methane particles T<sub>mp</sub>, i.e. to reducing its decay energy [6]:

$$T_{mp}(r) = T_0 \left(1 - \frac{d}{r}\right) \text{ for } d = \frac{2\delta V_0}{RT}, \quad (2)$$

where d is the critical radius starting from which the size effect takes place; T<sub>0</sub> is the melting point of the bulk sample; R is the universal constant, V<sub>0</sub> is the molar volume of methane, r is the particle radius, δ is the specific gravity of methane.

Expression (2) determines the decomposition rate of a coal-methane particle, i.e. methane release, which is caused by decreasing the surface tension, which is most typical for small particles of coal in the lower layer of the D<sub>6</sub> seam.

The process of the methane coal decomposition occurs under the effect of some external energy (thermal, mechanical, etc.) that occurs during the development of the seam and is an irreversible process.

The probability of dissipative processes is determined by the expression [7]:

$$P = \frac{2\Delta S}{k\tau} \exp \left\{ -\frac{E_m - G^0}{kT} \right\}, \quad (3)$$

where  $\Delta S$  is entropy changing in the dissipative process;  $E_m$  is the mean value of the molecule basic state energy;  $\tau$  is the relaxation time;  $G^0$  is the Gibbs energy,  $k$  is the Boltzmann constant ( $1.380649 \cdot 10^{-23}$  J/k),  $N$  is the Avogadro number.

The energy of decomposition (destruction) activation of the coal matter for the  $i$ -th gas is determined by the expression:

$$E_{ai} = \frac{E_{mi} - G_i^0 / C_i}{kT}, \quad (4)$$

where  $E_{mi}$  is the energy of the gas molecule activation,  $G^0$  is the Gibbs energy,  $T$  is the absolute temperature,  $C_i$  is the  $i$ -th gas molecules concentration.

Taking into account the Gibbs energy additivity for non-mutually acting particles:

$$G^0 = \sum_{i=1}^n C_i G_i^0; \quad C = \sum_{i=1}^n C_i; \quad E_m = \sum_{i=1}^n E_i, \quad (5)$$

From (5) it is obvious that the pure destruction of the coal matter is selective, and the function of gas emission is stepwise depending on  $E_{mi}$ ; the more gas or volatile molecules, the lower the activation energy.

Let's consider the part of gas emission that is associated with methane. In this case the activation energy of coal methane will have the form:

$$E_a = \frac{200 - G_y^0 / C}{kT}. \quad (6)$$

Here,  $E_m = 200$  kJ/mol is taken as the average binding energy of methane in coal matter. The activation energy for the decomposition of methane coal depends on the temperature, while the graph of gas evolution is also stepwise in accordance with  $E_{mi}$ .

Expression (6) based on the smallness of the ratio  $G^0/C$  for methane equal to  $536 \cdot 10^{-23}$ , where  $G_y^0$  is the Gibbs energy of the hydrocarbon, can be written by denoting the binding energy (or decay energy) of methane in the form  $G_y^0/C = E_m$ . From the ratio it follows that the lower the Gibbs energy of the hydrocarbon ( $G_y^0$ ), the lower the activation energy of coal-methane, so the temperature of the beginning of gas evolution, fusenite is 390°C, vitronite 335°C, enertite 250°C.

The average activation value for coals of varying degrees of metamorphism is determined - about 0.65 kJ/mol [7].

In work [4], a relationship was established between the gas evolution of methane ( $C$ ) and its initial concentration ( $C_0$ ) in the hydrocarbon (methane content) of the coal seam.

$$C = \frac{kT}{K_1} \frac{A}{G^0} M_0^2, \quad (7)$$

where  $A$  is the work (energy of external forces),  $K_1$  is a constant. The last equation characterizes the quadratic dependence of gas emission on the seam methane content ( $M_0$ ).

**Gas pressure in the seam.** In the natural state, in the coal matter there is a dynamic equilibrium between the adsorbed, absorbed and free phase methane, which is characterized by the fact that at any moment in the absence of extreme external impacts, the number of methane molecules passing from the free phase to the sorbed state is practically equal to the number of molecules of the desorbed methane. Free methane in the coal bed under natural conditions occupies a volume within which its and the molecules interaction with the coal surface is relatively low therefore, the volume of methane in the free phase in voids and cracks of coal is usually insignificant. Under such conditions, it plays the role of a "back-up" for sorbed methane preventing its desorption. Disruption of the dynamic equilibrium between methane in the free and sorbed phases in the natural system "coal – methane – natural moisture" during redistribution of rock pressure (under the impact of tectonic processes or mining operations) is manifested in increasing the number of desorbed methane molecules over the number of molecules that are sorbed by coal.

It has been established [8] that the volume of methane in the free phase at the depth of 700-1200 m in coals of medium metamorphism ( $V_{daf} = 18-19\%$ ) is from 5 to 10% of the total methane contained in coal, in coals of a high degree of metamorphism ( $V_{daf} = 18-14\%$ ) it is from 4 to 6%, and in slightly metamorphosed coals ( $V_{daf} = 30-38\%$ ) it is up to 10-12%. When the established dynamic equilibrium in the natural system «coal-methane-natural moisture» is violated, the movement of methane molecules from natural coal pores occurs both by moving along their walls, and by passing from an absorbed state to an adsorbed one and then to a free state, that is, the decomposition of methane coal occurs, accompanied by a decrease in the pressure of methane in coal [9, 10]. Since  $G_0 = H - TS + PV_1$  then at  $C - C_0$ , where  $C_0$  is the initial concentration of methane in the hydrocarbon (coal seam), and  $C$  is the current value of the methane concentration, we obtain the methane pressure in the seam equal to:

$$P = [C_0 - K_2(H - TS)] / (K_2V), \quad (8)$$

where  $H$  is enthalpy,  $S$  is entropy,  $K_2$  is a constant,  $V$  is the volume,  $T$  is the environment absolute temperature. The equation shows a complex dependence of gas pressure in the coal seam on its concentration and properties of the coal matter. It is seen that increasing the pressure increases the methane content of coal [10].

**Formation of cracks in coals.** Since characteristics of the methane content of the coal seam are associated with the surfaces and cracks of the massif, let us consider formation of cracks in coals as one of the reasons for its destruction including the instantaneous one, and formation of surfaces.

One of the important results of A. Griffiths [11] is the criterion he formulated for the destruction of a body with a crack, according to which the growth of a crack should be an energetically favorable process with energy conversion [12]. Let us express the condition of crack growth in the form of the energy balance:

$$\frac{\partial}{\partial l} (W - \Gamma) = 0, \quad (9)$$

where  $W$  is the potential energy of the plate deformation;  $\Gamma$  is the crack surface energy for a plate of a unit thickness,  $\Gamma = 4l\gamma$ ;  $l$  is the half length of the crack,  $\gamma$  is specific surface energy of destruction [3].

The condition of destruction can be written down as follows:

$$\frac{\partial W}{\partial l} \geq \frac{\partial \Gamma}{\partial l}. \quad (10)$$

From condition (10) it follows that a crack in a solid (coal mass) will develop during its deformation, that is, the action of rock pressure exerted on the coal seam, provided that the rate of the potential deformation energy release is greater than increasing the surface energy of the body, which is formed as a result of the formation of new surfaces.

Let's suppose that the crack element is determined by the product of a linear surface element by some function  $\Phi(u, v)$ , which depends on the stress state in the vicinity of this linear element [4]. For brittle fracture, this function should be proportional to the normal, highest stress ( $F$ ) or the highest linear deformation determined by Young modulus ( $E$ ) and the Gibbs potential ( $G$ ).

Thus, the trajectory of a crack is a geodesic line in the non-Euclidean space, the metric of which depends on the stress-strain state of the rock massif [4].

Then the Euler-Lagrange equation that can be used to obtain the equation of crack growth, takes the form:

$$\frac{\partial M}{\partial u} - \frac{d}{dv} \frac{\partial M}{\partial v'} = 0, \quad (11)$$

where  $M = \Phi(u, v) \sqrt{E + 2Fv' + G(v')^2}$ .

The behavior of stationary cracks can be described using the variation condition  $dE=0$ , and non-stationary using the equation  $\Phi(u, v)$

$$\int_{t_0}^t dEdt = 0, \quad (12)$$

where  $E = \int_{l_0}^{l(t)} \gamma ds$  is the functional reflecting the difference between the energy of absorption  $\int_0^{l(e)} \gamma ds$  consumed for the destruction and supply process  $\int_0^{l(t)} \varphi ds$  that is emitted with the crack growth,  $L = \gamma - \varphi$ . This functional can be considered as free energy or as the value proportional to the inner entropy increment.

The intensity of energy consumption for fracture ( $\gamma$ ) represents the energy required to form a unit area of the emerging new crack surface. The value of  $\gamma$  depends on the local resistance to separation of particles (petrographic composition of coals), plasticity, viscosity of the material and their change with the growth of the crack.

The intensity of the release of the supply energy arising in connection with increasing a unit area of the crack  $\varphi$  is spent on its formation, and only after the crack element formation the excess supply energy can be dissipated or transformed into kinetic energy.

The majority of natural mechanical systems in free motion dissipate the ordered kinetic energy of their motion and convert it into the chaotic thermal motion of molecules. Generally speaking, the total mechanical (potential+kinetic) energy in them decreases, passing into other forms (seismo-acoustic and electromagnetic, arising during the crack formation), they, ultimately, are converted into thermal energy. Such systems are called dissipative, and the process is called dissipation.

In case when the intensity of the supplied energy flow is such that the existing dissipation mechanism cannot cope with it, then such a system is destroyed due to the formation inside its elements, for a more intense energy dissipation. Such internal rearrangement leads to the internal dissipated structures formation with the aim of more intense dissipation of the energy supplied to the system. Their existence is possible only with a constant flow of energy from outside (rock pressure).

These processes form the conditions for the instant destruction of the coal massif.

**The coal mineral part effect on coal methane decomposition.** Coal seams contain heterogeneous minerals, such as: kaolin, albite, orthoclase, calcite, quartz, siderite, aragonite, magnesite and other various mineral inclusions.

For ideal solid solutions, the Gibbs energy is additive, then the activation energy of methane ( $E_a$ ) with the concentration of this gas ( $G$ ) molecules will have the form:

$$E_a = \frac{1}{C} \sum_{i=1}^n X_i G_i^0, \quad (13)$$

where  $X_i$  is the mole concentration of the coal mineral part component;  $C$  is the methane molecules concentration in coal;  $G_i^0$  is the Gibbs energy of the  $i$ -th component.

From formula (13) it follows that increasing the proportion of the mineral part of coal, especially oxides, leads to increasing the activation energy and, consequently, to inhibiting the decomposition of coal methane.

### Conclusion

The initial gas content of the D<sub>6</sub> seam at the Kazakhstanskaya and Lenin mines is 18 m<sup>3</sup>/ton, and the D<sub>6</sub> seam is gas-bearing, despite the high ash content. Natural seam pressure at the depth of 683 m is about 4.5 MPa. This is the reason for the high associated gas content, which is 67% of the hydrostatic pressure for the depth of 683 m.

The lower layer of the seam consists of highly outburst-prone coal. In general, the D<sub>6</sub> seam is considered to be sufficiently connected to the lower layer so that the initial gas pressure remains the same throughout the entire seam thickness. Variations in the petrophysical characteristics of the seam and the seam gas are associated with geological conditions, such as tectonic faults, folding, the presence of a crushing zone, etc. Possible increasing the in discharge during drainage of the seam is a sign of the effect of drainage or increasing permeability caused by coal shrinkage.

Drilling in the D<sub>6</sub> seam can be complicated by the soft coal of the lower layer, which has shear disturbances, and it is possible that the wells that cross this soft coal will be complicated during drilling with flushing, since sticking is possible in this interval, and there is also a high probability of the drilling tools loss, inclinometers for directional drilling.

A hyperbolic dependence of the complete disintegration of a coal particle on the ratio of the difference in the concentration of methane in the particle at its boundary and in the distribution has been established.

The energy of decomposition of the coal substance has been determined depending on the activation energy and the concentration of methane, the temperature and the Gibbs energy of the carbohydrate.

The regularity of changing the gas pressure in coal depending on the initial concentration of methane and the thermodynamic parameters of the system has been obtained.

The regularities of the crack formation in coals have been, which are determined by the destruction energy spent on the formation of a unit surface area of a new crack and the supply energy arising from increasing a unit area of the crack, while excess energy can dissipate or transform into kinetic energy.

The total mechanical energy, when exposed to loads decreases when passing into seismo-acoustic and electromagnetic energy, and ultimately into thermal energy.

It has been found that the ash content of coals leads to increasing the activation energy for methane emission from them, i.e., to inhibiting the decomposition of coal methane.

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## Д<sub>6</sub> көмір қабатының газдылығы

Мақалада Тентек ауданындағы ең қуатты және тұрақты Д<sub>6</sub> көмір қабатының газдылығы мәселелері қарастырылған. Бұл күрделі құрылым қабаты жерасты қазбаларында газ бен шаң үшін қауіпті, ол сазтас қабаттарымен бөлінген көмір қабаттарынан тұрады, ал төменгі қабаты 0,5-1,5 м өте жұмсақ, ығысудың қатты бұзылысына ие және метанмен қаныққан. Көмір қабаттарынан метанды өндіру — шахталардағы тау-кен жұмыстарының қауіпсіздігін қамтамасыз ету, оның атмосфераға шығарылуын төмендету және синтетикалық материалдарды алу үшін оны отын және өнім ретінде пайдалану үшін қажетті процесс. Жоғарғы, қуатты қабаттың және төменгі жұқа қабаттың гранулометриялық құрамының өзгеру заңдылығы ондағы көмірдің кішкене бөлшектерінің айырмашылығын көрсетеді, ал олардың төменгі қабатында олардың көп мөлшері бар, демек, меншікті беті үлкен, бұл метанның жиналуындағы және газды құрғату кезінде адсорбциялық процестердің қарқындылығының маңызды факторы. Көмір заттарынан метанды белсендіру энергиясы анықталды. Метан газының бөлінуі мен оның бастапқы концентрациясы арасындағы квадраттық байланыс көрсетілген. Көмір затында бұл сыртқы күштердің энергиясына байланысты. Көмір қабатындағы газ қысымы оның концентрациясымен және «көмір-метан-табиғи ылғалдылық» жүйесінің сипаттамалары арасындағы күрделі байланыс анықталған. Көмір қабатының метандылығының жарықшақ бұрышында байқалатын аудан өсімімен пайда болатын энергия

мен энергияның ыдырауы әсерінен қалыптасатын, оның жарықшақтылығынан өзгеру заңдылықтары алынды. Көмірдің минералды құрамының газ құрамына әсері көрсетілген.

*Кілт сөздер:* метан, гранулометриялық құрам, жарықшақтық, дренаж, ұңғыма, энергияның ыдырауы.

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## Газоносность угольного пласта D<sub>6</sub>

В статье рассмотрены вопросы газоносности самого мощного и устойчивого угольного пласта D<sub>6</sub> в Тентекском районе. Данный пласт по типу сложного строения, опасен при подземной добыче по газу и пыли. Состоит из угольных пачек, разделенных прослоями аргиллитов, при этом нижний слой мощностью 0,5–1,5 м очень мягкий, имеет сильное сдвиговое нарушение и наиболее насыщен метаном. Извлечение метана угольных пластов является необходимым процессом для обеспечения безопасности ведения горных работ в шахтах, снижения его выброса в атмосферу, утилизации в качестве топлива и продукта для получения синтетических материалов. Закономерность изменения гранулометрического состава верхней мощной пачки и нижней тонкой свидетельствует о различии в них мелких частиц угля, при этом в нижнем слое их значительно больше, и, следовательно, удельная поверхность больше, что является важным фактором интенсивности адсорбционных процессов накопления метана и при дренировании газа из пласта. Определена энергия активации метана из углеводорода. Показана квадратичная связь между газовыделением метана и его начальной концентрацией. В углеводороде она зависит от энергии внешних сил. Установлена сложная связь между давлением газа в пласте угля от его концентрации и характеристик системы «уголь–метан–природная влага». Получены закономерности изменения метаноносности угольного пласта от его трещиноватости, формируемой за счет влияния энергии разрушения, и энергии, появляющейся с приростом площади трещины, возникающей в угле. Показано влияние минерального состава угля на его газоносность.

*Ключевые слова:* метан, гранулометрический состав, трещиноватость, дренаж, скважина, энергия разрушения.

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