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About the Necessity for Changing the Methodical Approach to the Calculation of Methane Release Rate in High-Performance Working Faces of Kuzbass

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Abstract: It is traditionally believed that the use of high-performance mining equipment in collieries leads not only to increasing productivity of the enterprise, but also to significant increasing release of methane into the mine air. Based on this, the existing regulatory and methodological support for calculations allowed predicting the rate of methane release into the mine air and determining the required operating modes of the ventilation system to ensure mining safety. The task of this study is to investigate in practice the laws of methane release as a function of the productivity of mining equipment and to identify phenomena that affect the nature of these laws. Based on the data of air gas monitoring, the results of statistical study of methane release in 101 working faces of 33 collieries of Kuzbass are presented. In 76 working faces, parabolic law of the dependence of the methane release on the productivity of mining equipment, having peak points in relation to the rate of advance and productivity of the shearer were established with high confidence. Using the law of A. Darcy and the equation of sorption of I. Langmuir, it has been theoretically established that methane release from loose coal is a function inversely proportional to the linear hyperbolic dependence, and also has a peak point in relation to the rate of advance and productivity of the shearer. Analysis of the established dependence of the rate of methane release from the loose coal shows that the methane release significantly (quadratically) decreases with decreasing the rotational speed of the cutting auger and the number of cutters in the cutting line or the number of blades on the drum. Methane release also quadratically increases with increasing formation thickness and the shearer cutting width. The extreme dependence of the rate of methane release from loose coal forms two areas of allowable rate of advance and productivity of the shearer by gas factor.

Keywords: mine, coal seam, methane release, methane concentration, statistical analysis, permissible performance of working face, gas content, shearer rate of advance, fractional yield.

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О необходимости изменения методического подхода к расчету дебита метана в высокопроизводительных очистных забоях Кузбасса

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Аннотация: Традиционно считается, что использование высокопроизводительного добычного оборудования на угольных шахтах приводит не только к увеличению производительности предприятия, но и к значительному повышению выделения метана в рудничную атмосферу. Исходя из этого существующее нормативно-методическое обеспечение для расчета позволяло прогнозировать дебит метана в рудничную атмосферу и определять необходимые режимы работы системы проветривания для обеспечения безопасности горных работ. В работе поставлена задача исследовать на практике закономерности метановыделения от производительности добычной техники и выявить явления, влияющие на характер этих закономерностей. На основании данных средств аэрогазового контроля приведены результаты статистического исследованияметановыделения в 101 очистном забое 33 шахт Кузбасса. С высокой степенью достоверности в 76 очистных забоях установлены параболические зависимости метановыделения от производительности добычной техники, имеющие точки максимума относительно скорости подачи и производительности очистного комбайна. С использованием закона А. Дарси и уравнения сорбции И. Ленгмюра теоретически установлено, что метановыделение из отбитого угля является функцией, обратно пропорциональной линейно-гиперболической зависимости, а также имеет точку максимума относительно скорости подачи и производительности очистного комбайна. Анализ установленной зависимости дебита метана из отбитого угля показывает, что метановыделение значительно, в квадратической зависимости, снижается при уменьшении частоты вращения шнека и количества резцов в линии резания или количества лопастей на шнеке. Метановыделение также в квадратической зависимости растет с увеличением мощности пласта и ширины захвата комбайна. Экстремальная зависимость дебита метана из отбитого угля формирует две области допускаемых значений скорости подачи и производительности очистного комбайна по газовому фактору.

Ключевые слова: шахта, угольный пласт, метановыделение, концентрация метана, статистический анализ, допускаемая производительность очистного забоя, газовый фактор, скорость подачи комбайна, выход фракций.

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Introduction.

Modern imported shearers used in Kuzbass collieries are equipped with high-power electric drives and have significant productivity and feed speed. For example, Eickhoff SL-900 shearer weighing 90 tons, used at Named after V.D. Yalevsky colliery, has total power of cutting and feed drives electric motors of 2104 kW. The shearer feed speed reaches 48 m/min, and the productivity exceeds 50 kt of coal per day. In August 2018, at the Named after V.D. Yalevsky colliery, in longwall 5004 400 m long while extracting a seam 3.8 m long, world record in coal production was achieved, 1627 kt.

However, at the same time, the operation of modern auger shearers, scraper conveyors, and crushers in the production faces leads to overgrinding of coal. Under the conditions of

Kostromovskaya colliery, 69.1 % of coal is produced in grain sizes "culm" (0–6 mm) and "flaxseed coal" (6–13 mm). The similar picture of prevailing fine coal fractions yield is present at many other mines. This leads to a number of negative consequences: decreasing rank and, correspondingly, wholesale price of coal, as well as increasing yield of dust fractions and methane release from the loose coal in production faces.

Patterns of the methane release intensity depending on productivity of mining equipment at coal mines.

One of effective ways for reducing methane release in production faces is increasing productivity of auger shearers. Decreasing methane release from loose coal at high performance of a shearer was first recorded by specialists of Scientific Center "VostNII" in 2010 using air and gas monitoring devices at "Tagaryshskaya", "Kotinskaya", "Taldinskaya-Zapadnaya-1" collieries [1]. The essence of this phenomenon is that, with increasing the shearer feed speed and productivity, in the initial period methane release from the loose coal increases, almost in accordance with the estimates based on the approved instructions and methods [2–4], and then, after reaching a certain maximum rate of methane release, at further increasing the shearer productivity, methane release decreases. Given high productivity of a shearer (20–30 ktpd or more), there is a significant discrepancy between the actual release of methane in the production faces and the estimated release [1]. For example, at Kotinskaya colliery, the discrepancy between the estimated and actual (obtained by means of air-gas monitoring) methane release data at the production face is more than 5 times at coal productivity of 30 ktpd, whereas at the productivity of 37 ktpd the estimated methane release exceeds the actual one by more than 15 times (Fig. 1)!

This phenomenon contradicts the approved instructions [2–4] and requires more complete theoretical and statistical investigation.

Based on the information obtained by devices of air-gas monitoring, the authors conducted a statistical analysis of the actual methane release in 101 production faces of 33 Kuzbass collieries. The analysis allowed determining, with high confidence, based on 76 production faces data, parabolic dependencies of methane release rate on the shearer productivity, demonstrating peak points (Table 1, Fig. 2).

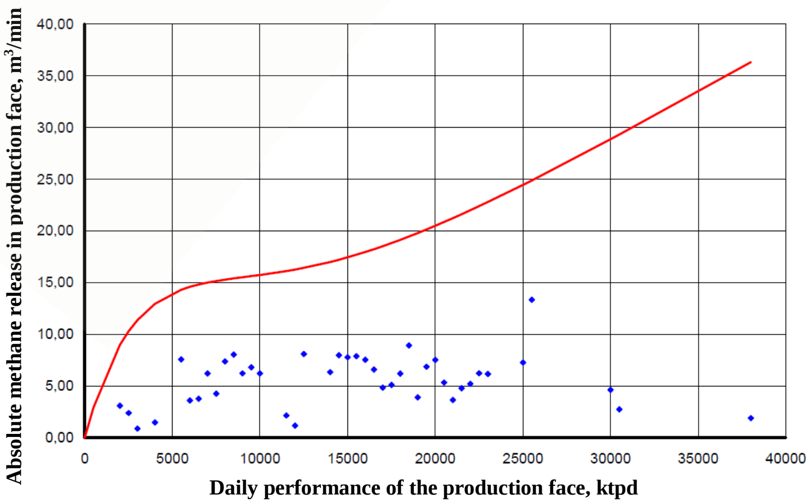

Fig. 1. Theoretical methane release curve in accordance with applicable instructions and the factual methane release rate in production face 5203 of the Kotinskaya colliery

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The tendency to decreasing methane release from loose coal is individual for each seam and production face. For example, for the S. M. Kirov colliery, when extracting the Boldyrevsky seam, the decrease in methane release starts at the productivity of 6 ktpd for production face No. 24–40, 10 ktpd for production face No. 24–45, and 11 ktpd for production face No. 24–57.

Thus, the statistical analysis conducted for 76 production faces confirms with high confidence the trend of decreasing absolute methane release from loose coal at high productivity of a face.

Substantiation of methane release intensity models for collieries. Experimental findings and their discussion. A theoretical explanation of the decrease in methane release from loose coal at high shearer productivity was given by the authors in [6, 7]. The essence of this phenomenon is that increasing the shearer feed speed and productivity results in changing the loose coal fractional composition. Namely, the yield of fine fractions decreases, whereas the yield of coarse fractions increases. The dependences of the yield of size fractions on the feed speed on the basis of the statistical data [5] are linear, and the total methane release rate from all fractions of the loose coal in accordance with Darcy's law is determined in this case by parabolic dependence on the shearer feed speed:

$$Q(v)=\frac{180vmrk_1(P-P_a)}{\mu}\sum_{i=1}^{k}\frac{\beta_i(v)}{R_i^2}=\frac{180vmrk_1(P-P_a)}{\mu}\sum_{i=1}^{k}\frac{\pm a_i v+b_i}{R_i^2}=180mrk_1\mu^{-1}(P-P_a)(-cv^2+d), \quad (1)$$

where k is the number of loose coal fractions; v is the shearer feed speed, m/min; m is the seam thickness, m; r is the shearer cut (web) width, m; k_1 is the coal permeability coefficient; P, P_a are the pore pressure of the gas inside the coal particle and atmospheric pressure in the face, P_a, respectively; μ is absolute viscosity of the medium along the methane filtration path, P_a·s; $\beta_i(v)$ is the dependence of the i-th fraction yield on the shearer speed, %; R_i is the average particle radius of the i-th loose coal fraction, m; a_i, b_i are the coefficients of the linear dependences of the yield of fractions on the shearer feed speed; c, d are the coefficients of the parabolic dependence of the total methane release rate on all the coal fractions yield.

Thus, based on the statistical analysis of air-gas monitoring data for 76 Kuzbass production faces and taking into account the statistical data on the yield of different coal size fractions, the parabolic dependence of methane release from the loose coal on the shearer feed speed and productivity, with a peak value, was established.

Similar parabolic dependences were obtained in [8] on the basis of the statistical analysis of operation of production faces at the Mine named after A.F. Zasyadko in Donbass.

It should be noted that all the parabolic dependences of the methane release on the shearer productivity were obtained using statistical methods and, despite the rather high regression confidence, still do not reveal the physics of this phenomenon.

The statistics do not explain the physical process of reducing methane release at high shearer feed speed and productivity.

A theoretical explanation of this effect was given by the authors in [7], in which, based on Darcy law and Langmuir sorption equation, as well as on the relationship between the feed speed and the chip thickness and the auger (cutting drum) rotation speed, extremum (having peak points) dependences of the methane release on the shearer feed speed (v) and productivity (A) were derived:

$$Q(v)=\frac{720mrk_1\left(0.9X\left(1+bP_a\right)-abP_a\right)}{\mu b\left(a-0.9X\right)\left(\frac{v}{(\pi nn_1)^2}+\frac{h_p}{\pi nn_1}+\frac{0.25h_p^2}{v}\right)},\ \text{m}^3/\text{min},$$
$$Q(A)=mLq+\frac{720k_1\left(0.9X\left(1+bP_a\right)-abP_a\right)_a}{\mu b\left(a-0.9X\right)\left(\frac{A}{\gamma(mr\pi nn_1)^2}+\frac{h_p}{mr\pi nn_1}+\frac{0.25\gamma h_p^2}{A}\right)},\ \text{m}^3/\text{min},\quad (2)$$

where a, b are Langmuir isotherm constants, determined for coal based on [10]: a = 49.3 m^3/t, $b = 0.207\cdot10^{-6}$ 1/Pa; n is auger rotation frequency, min^{-1}; n_1 is the number of cutters on the auger blades in one cutting line; h_p is the distance between the cutters on the auger blades; X is the coal natural methane content, m^3/t; L is the face length, m; q – methane release rate from coal seam, m^3/min; γ – coal mass density, t/m^3.

Table 1

Regression dependences of methane release (Q, m³/min) from the loose coal on the productivity (A, t/day) of a shearer

No.	Production face	Regressional dependence	Approximation coefficient, R^2	Regression coefficient, R	Population size	Standard deviation, σ	Coefficient of relationship reliability, $k = R/\sigma > 3$
		S.M. Kirov Colliery					
		Boldyrevsky seam					
1	24-40	$Q = -1\cdot10^{-7}A^2 + 0.0012A + 0.443$	0.94	0.97	13	0.017	58.26
2	24-45	$Q = -3\cdot10^{-8}A^2 + 0.000$[illegible]$A + 0.855$	0.84	0.92	20	0.036	5.62
3	24-57	$Q = -5\cdot10^{-8}A^2 + 0.0011A + 1.02$	0.82	0.91	14	0.048	18.82
4	24-59	$Q = -1\cdot10^{-7}A^2 +$ [illegible]$A + 2.42$	0.69	0.83	25	0.062	13.40
		Polenovsky seam					
5	25-85	$Q = -3\cdot10^{-8}A^2 + 0.0008A + 1.225$	0.89	0.94	20	0.025	38.35
6	25-86	$Q = -7\cdot10^{-8}A^2 + 0.001A + 0.$[illegible]$54$	0.9	0.95	18	0.024	40.25
		Zarechnaya Colliery, Polysaevsky-1 seam					
7	904	$Q = -2\cdot10^{-8}A^2 + 0.0005A + 0.632$	0.74	0.86	16	0.068	13.23
		Yesaulskaya Colliery, seam 26a					
8	26-30	$Q = -1.5\cdot10^{-7}A^2 + 0.0015A + 0.64$	0.8	0.89	11	0.06	14.83
9	26-18	$Q = -3\cdot10^{-8}A^2 + 0.001A + 1.341$	0.8	0.89	10	0.063	14.14
		Abashevskaya Colliery, seam 64					
10	64-204	$Q = -1.56\cdot10^{-7}A^2 + 0.0012A + 0.61$	0.74	0.86	13	0.072	11.93
		Taldinskaya-Zapadnaya Colliery, seam 67					
11	67-04	$Q = -1\cdot10^{-7}A^2 + 0.0017A + 0.45$	0.85	0.92	15	0.039	23.8
		Kotinskaya Colliery, seam 52					
12	5203	$Q = -7\cdot10^{-9}A^2 + 0.0003A + 3.02$	0.17	0.41	52	0.115	3.6
13	5209	$Q = -1\cdot10^{-8}A^2 + 0.0008A + 6.02$	0.59	0.77	49	0.059	13.1
		Named after V.D. Yalevsky colliery, seam 52					
14	5210	$Q = -7\cdot10^{-9}A^2 + 0.0005A + 1.64$	0.63	0.79	41	0.058	13.74
		Named after 7 November Colliery, Baikaimsky seam					
15	1380	$Q = -3\cdot10^{-8}A^2 + 0.0007A + 0.97$	0.54	0.73	26	0.09	8.15
		Taldinskaya-Zapadnaya Colliery, seam 70					
16	70-06	$Q = -7\cdot10^{-9}A^2 + 0.0002A + 0.97$	0.49	0.7	31	0.092	7.64
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		Raspadskaya Colliery, seam 10					
76	4-1029	$Q = -3\cdot10^{-8}A^2 + 0.001A + 1.64$	0.93	0.96	26	0.014	70.25

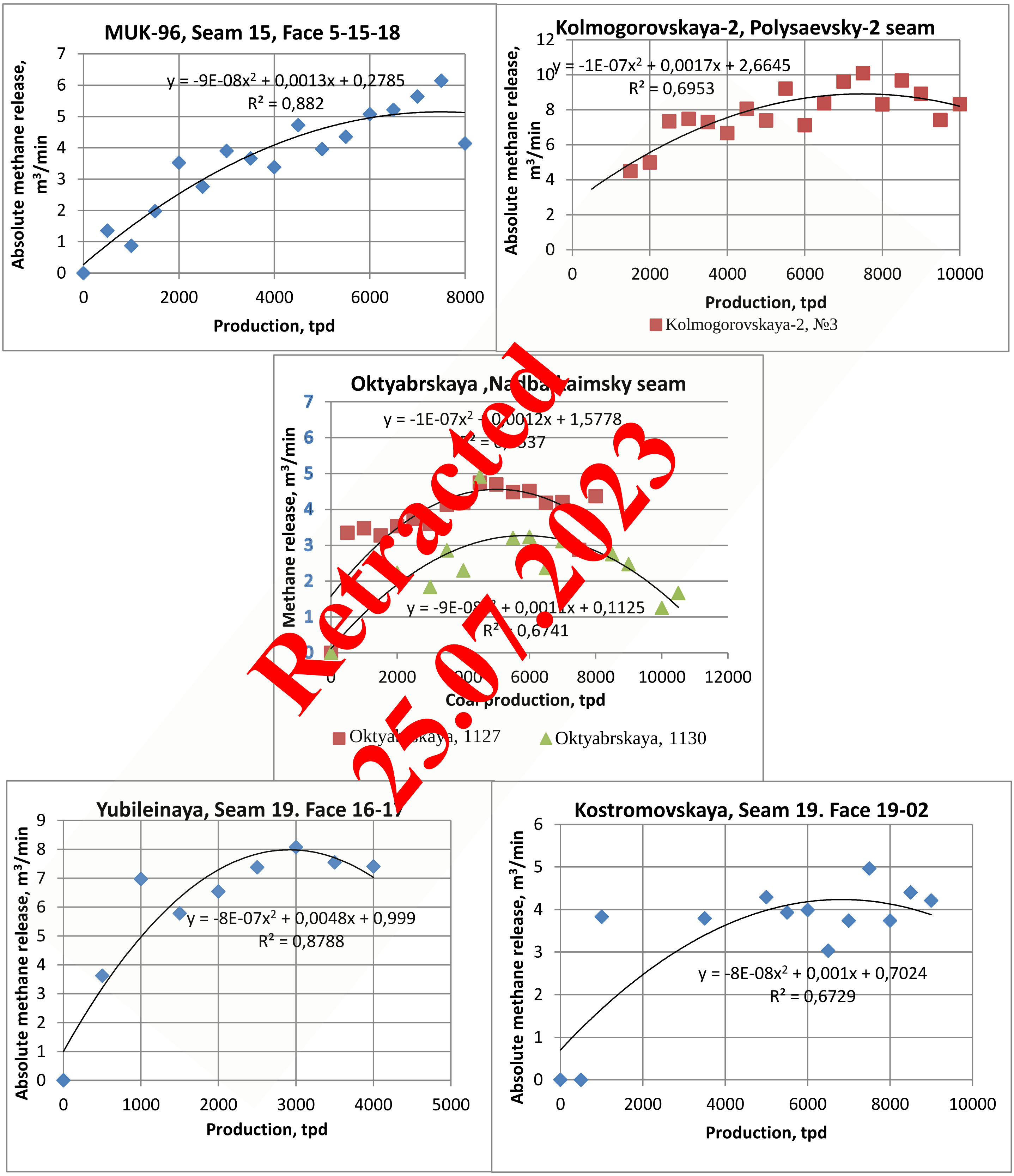

Fig. 2. Actual data and regression dependences of absolute methane release on the working face performance at the MUK-96, Kolmogorovskaya-2, Oktyabrskaya, Yubileynaya, Kostromovskaya collieries

Analysis of dependences (2) shows that methane release from loose coal demonstrates inversely proportional linear-hyperbolic dependence on the shearer feed speed and productivity, having a peak point (Fig. 3). As can be seen in Fig. 3, this theoretical methane release curve (2) describes well the data on the actual methane release in the face and differs significantly from the normative dependence shown in Fig. 1. Methane release from loose coal significantly (quadratically) decreases with decreasing the rotational speed of the auger (cutting drum) and the number of cutters in the cutting line or the number of blades on the auger (drum). Methane release also quadratically increases with increasing seam thickness and the shearer cutting width.

In connection with the existence of a methane release rate maximum point, the methodology for estimating permissible productivity (performance) of a production face by gas factor should be changed. According to the existing instructions [2–4], the value of the maximum permissible productivity (A_{max}) of a face is estimated by the formula:

$$A \le A_{max} = \frac{0.6 v_{max} S k_{oz} c}{k_e K_{пл}(q - q_o) K_{WA}}, \text{ t/min}, \quad (3)$$

where v_{max} = 4 m/s is the maximum air stream speed in a face allowed by the safety rules [11]; S is the inner cross-sectional area, m^2; k_{oz} = 1.05 ÷ 1.30 is the coefficient taking into account air leaks into the mined-out space; c = 1 % is the permissible concentration of methane in the return ventilation air from a longwall according to the Safety Rules; q, q_o are the natural and residual methane content of coal, m^3/t, respectively; K_{WA} is the coefficient taking into account the coal natural moisture and ash content; k_e is the coefficient of natural coal mass outgassing in a shearer cut.

As can be seen in Fig. 4, the extremum function of methane concentration forms an area of acceptable values of the shearer feed speed and productivity:

$$v_{min} < v < v_{max}; \quad A_{min} < A < A_{max}; \quad A_{max} = \gamma m r v_{max} \quad (4)$$

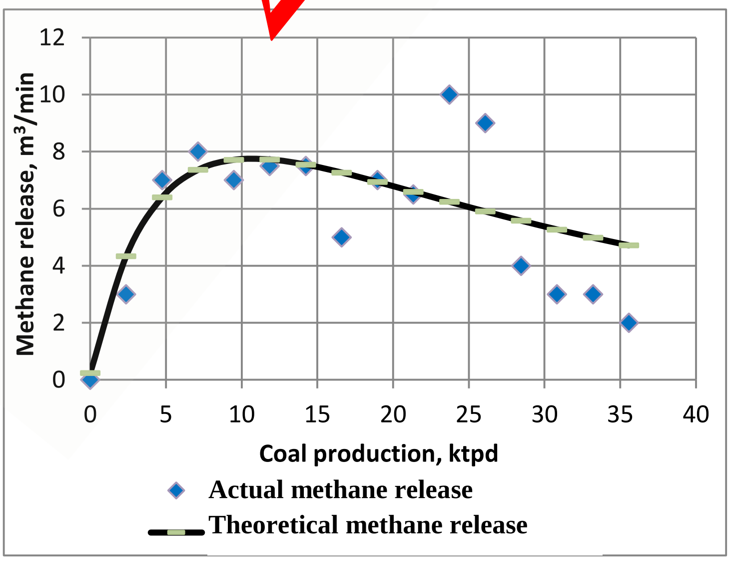

Fig. 3. Theoretical dependence (2) and actual methane release in longwall 5203 of the Kotinskaya colliery

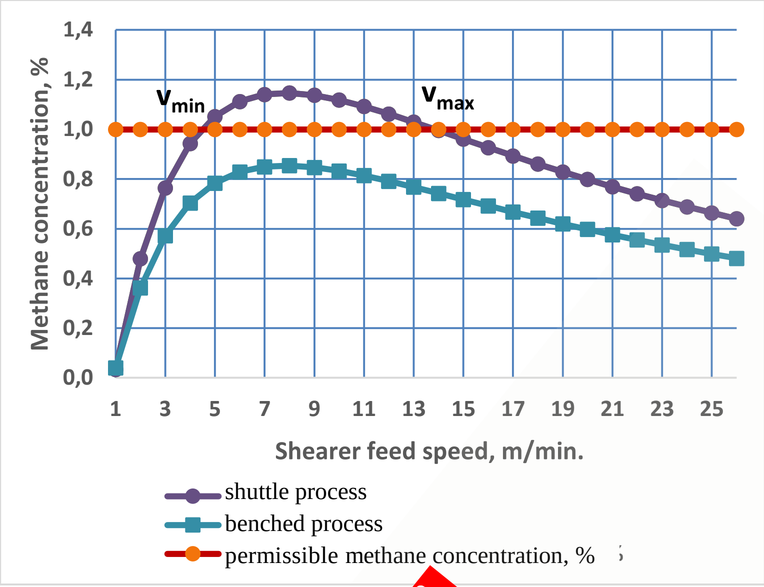

Fig. 4. Dependencies of methane concentration in upcast in longwall 5005 of the Named after V. D. Yalevsky colliery on shearer rate of advance for shuttle and benched process flow sheets

and, correspondingly, the area of the permissible shearer feed speed and productivity by gas factor is determined by meeting one of two conditions, depending on the shearer capacity:

$$A < A_{min} \vee A > A_{max}, \quad (5)$$

where v_{min}, v_{max}, A_{min}, A_{max} are the boundary values of the shearer feed speed and productivity based on the gas factor.

In particular, for longwall 5005 of the Named after V.D. Yalevsky colliery, these boundary values for the shuttle PFS are as follows (Fig. 4):

v_{min} = 4.8 м/мин, v_{max} = 14.0 м/мин;

A_{min} = 19.5 т/мин, A_{max} = 57 т/мин.

At the Named after V.D. Yalevsky colliery, the option of the maximum permissible performance (productivity) of the production face was implemented, and the extraction panel of seam 50 was extracted at the shearer SL-900 speed exceeding 14 m/min and daily performance of more than 50 ktpd.

It is obvious that the process safety of the entire coal mining enterprise will depend on methane release regimes. A significant number of studies are devoted to this issue in Russia and abroad, but solving the problems of process safety always requires reliable methane release estimation model based on the process parameters of mining operations [10-20].

Conclusions

Based on the statistical analysis of air-gas monitoring data for 76 Kuzbass production faces, the parabolic dependence, having a peak point, of methane release from the loose coal on a shearer feed speed and productivity was established with high confidence.

A theoretical explanation of the effect of reducing methane release from loose coal at a high productivity of the shearer is that increasing the shearer feed speed and productivity results in changing the loose coal fractional composition, namely, the yield of fine fractions decreases whereas the yield of coarse fractions increases.

It was theoretically established using Darcy's law and Langmuir sorption equation that methane release from loose coal demonstrates inversely proportional linear-hyperbolic dependence on the shearer feed speed and productivity, having a peak point.

Analysis of the established dependence of the rate of methane release from the loose coal shows that the methane release significantly (quadratically) decreases with decreasing the auger (cutting drum) rotational speed and the number of cutters in the cutting line, or the number of blades on the auger (drum). Methane release also quadratically increases with increasing seam thickness and the shearer cutting width.

The extremum dependence of the rate of methane release from loose coal forms two areas of permissible shearer feed speed and productivity by gas factor.

Thus, it is necessary to revise the existing methodological approaches to estimating methane release in high-performance production faces in order to take into account the extremum dependence of methane release on a shearer feed speed and productivity, and, when estimating the permissible productivity of a production face by gas factor, the possibility of reducing methane release at significant increasing a shearer feed speed and productivity should be taken into account.

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