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ESTABLISHING THE INTERRELATION OF THE MAIN INFLUENCING FACTORS ON THE SAFETY OF METHANE-AIR MIXTURE TRANSPORTATION

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ВСТАНОВЛЕННЯ ВЗАЄМОЗВ'ЯЗКУ ОСНОВНИХ ФАКТОРІВ, ЯКІ ВПЛИВАЮТЬ НА БЕЗПЕКУ ТРАНСПОРТУВАННЯ МЕТАНОПОВІТРЯНОЇ СУМІШІ

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УСТАНОВЛЕНИЕ ВЗАИМОСВЯЗИ ОСНОВНЫХ ФАКТОРОВ, ВЛИЯЮЩИХ НА БЕЗОПАСНОСТЬ ТРАНСПОРТИРОВАНИЯ МЕТАНОВОЗДУШНОЙ СМЕСИ

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Annotation. The results of main mining geological and technological factors interrelation affecting the safety of methane-air mixture transportation in the extraction of coal deposits are shown in article. The calculation of the pipeline diameter and the choice of a vacuum pump for capturing methane-air mixture from underground wells in a real mine is presented. The transportation safety conditions of methane-air mixture are presented. The influence of the methane-air mixture parameters on the safety of the degassing system is considered using the data of the MM "Sukhodolskoye-Vostochnoye", where the gas mixture is transported through degassing pipes which laid in the mine workings and is carried out due to the operation of the vacuum pump. The interrelation between mining geological and technological factors that affect at the safety of methane-air mixture transportation using regression analysis is established. The analysis took into account precisely regulated factors. They include: the flow rate of the methane-air mixture in the division, the length of the gas pipeline in the extraction division, the atmospheric pressure in the mine, the depth of the working, the density of the methane-air mixture and the diameter of the pipeline. When determining the interrelation between the main factors affecting the safety of transportation of methane-air mixture, it was found that the maximum impact is exerted by the consumption factor of the methane-air mixture at the starting point of the gas pipeline. As a result, linear multiple regression was obtained, which made it possible to establish the effect of the methane-air mixture flow at the starting point of the gas pipeline on safe conditions for its transportation. The resulting model of value calculation corresponds to the original data of value original and is described with an accuracy of 95 %.The obtained results make it possible to predict changes in the safe transporting conditions of methane-air mixture and subsequently manage them when the methane consumption from the boreholes changes with the aim of uninterrupted and trouble-free operation of the degassing gas pipeline.

Keywords: methane emission, methane-air mixture, gas pipeline diameter, mining and geological factors, development of coal deposits, regression model.

Introduction. There is a shortage of gaseous energy carriers, which is caused by the limited nature of their reserves and the substance volumes lag of the consumption volumes production in the fuel and energy complex of Ukraine. The intensive technologies development of mining enterprises, an uprating of mechanized excavation harvesters and planes increase the load on the working faces, and the development of mineral resources is conducted in increasingly complex mining and geological conditions. The gas factor is the main reason for limiting the extraction of district production. In the conditions of mines with a high volume of gas, the presence of a "gas barrier" reduces the efficiency of the existing high-performance equipment. Earlier in the coal industry, the main attention was paid to improving the technology and technics of coal mining. Gas control was assigned a secondary role. Currently, the main task is to improve the safety of mining operations [1, 2]. A secondary task is the extraction of coal mine methane during the shortage of an alternative source of energy.

About 360 million cubic meters of methane (26 %) are recovered by mine degassing systems, about 50 % of which is captured and usefully used [3]. Degassing in coal mines is carried out by drilling vertical wells from the surface, as well as from mine workings to a gas-saturated coal-rock massif. To transport and evacuation of methane through metal pipelines, vacuum pumping units, and gas suction fans are used. According to the norms, the concentration of methane in the degassing pipelines should be at least 25 % in a mixture with air, and the concentration of methane in the air stream leaving the mine should not exceed 0.75 % according to safety conditions [4]. It is impossible to ensure an increase in coal mining and the profitability of mines without degassing. Therefore, the establishment of the main influencing factors interrelation on the safety of transportation of methane-air mixture is relevant.

Methods. The calculation of the diameter of the pipeline and the choice of a vacuum pump for capturing methane-air mixture from underground boreholes is carried out according to [5]. Determining the interconnections of the main influencing factors on the safety of transportation of methane-air mixture is feasible with the help of multiple regressions [6].

Determine the flow of methane-air mixture in the pipeline

$$Q_s = k_r \cdot (Q_0 + k_n \cdot l_w)\ ,\ \text{m}^3/\text{min} \tag{1}$$

where k_r - the safety factor, taking into account the error of the prediction of methane emission, $k_r = 1.25$; Q_0 - the flow of methane-air mixture at the starting point of the pipeline, m^3/min (from boreholes); k_n - coefficient taking into account the air leakage per 1 m of the pipeline, 10-3 m^2/min; l_w - the length of the gas pipeline working area, m.

Determine the concentration of methane gas in the pipeline

$$C_a = \frac{100 \cdot I_0}{Q_0 + k_n \cdot l_w}\ ,\% \tag{2}$$

where I_0 - the emission of methane entering the gas pipeline at the working area, m^3/min.

Determine the pressure in the pipeline

$$P_p = P_b \cdot \left(1 + 1.17 \cdot 10^{-4} \cdot H\right) - B_y,\ \text{mm Hg} \tag{3}$$

where P_b - atmospheric pressure in the mine, measured by a barometer, 760 mm Hg; B_y - vacuum in the borehollheads, 50 mm Hg; H - depth of development, m.

Determine the unit pressure loss in the pipeline

$$\Delta P_u = \frac{760 - P_m - B_y}{l_w}, \text{ (mm Hg)/m} \quad (4)$$

where P_m - the pressure of the methane-air mixture at the suction inlet of the vacuum pump, mm Hg, P_m = 300 mm Hg - when designing degassing systems.

Determine the diameter of the pipeline

$$d = 0.04 \cdot \left(\frac{Q_s{}^2}{\Delta P_u} \right)^{0.188}, \text{ m} \quad (5)$$

We determine the internal diameter of the injection pipeline, which supplies the gas-air mixture from the vacuum pumping station to the boiler room. The distance from the surface degassing complex to the boiler room is 200 m. The actual diameter of the pipeline is 273 mm. The calculation was produced by formula [5]

$$d_i = \sqrt{\frac{\left(\frac{V_\mathrm{g}}{Q_\mathrm{g}} + t_\mathrm{g} + t_\mathrm{i} \right) \cdot Q_\mathrm{u}}{47 \cdot l_g}}, \text{ m} \quad (6)$$

where V_g - the volume of the way along which the methane-air mixture passes from the place of sampling to the entrance to the gas analyzer, m^3; Q_g - the flow of methane-air mixture passing through the gas analyzer, m3/s; t_g - total inertia (including transport and preparation of methane-air mixture) of the gas analyzer, s; t_i - inertia of the slam-shut valve, 0.5 s; Q_u - the flow of methane-air mixture supplied to the user, m^3/s; l_g – the length of the discharge pipe, m.

Determine the pressure methane-air mixture in the discharge pipe of the pump on formula [5]

$$P_i = \Delta P_a + \Delta P_d + \Delta P_m + P_g + P_n, \text{ mm Hg} \quad (7)$$

where ΔP_a - the pressure loss in the protective and regulating equipment, mm Hg; P_n - pressure loss on flame arresters, 10 mm Hg; ΔP_d - pressure loss at the measuring diaphragm, 5 mm Hg; ΔP_m - pressure losses due to friction in the pipeline, mm Hg.

The pressure loss in the protective equipment determined by empirical formula

$$\Delta P_a = k_a \cdot Q_0^2 \cdot \gamma_c, \text{ mm Hg} \quad (8)$$

where k_a - the coefficient equal to 0.009 (pipe diameter of 0.273 m); γ_c - the density of the methane-air mixture, kg/m^3

$$\Delta P_m = \sqrt{P_g^2 + \frac{4.8 \cdot 10^{-5} \cdot l_{gp} \cdot Q_0^2 \cdot \gamma_c}{d_d^{5.33}}} - P_g, \text{ mm Hg} \quad (9)$$

where P_g - the methane-air mixture pressure in the burners, mm Hg; l_{gp} - the length of the injection pipeline, m; d_d - the diameter of the injection pipeline, m.

The pressure in the discharge nozzle of a vacuum pump can exceed atmospheric pressure by no more than 180 mm Hg

$$P_i - P_b < 180 \text{ mm Hg – the compliance condition} \qquad (10)$$

Determination of the degree of influence of the parameters of the meta-air mixture under these conditions will be carried out using the multiple regression equation.

The multiple regression equation can be represented as

$$Y = f(\beta, X) + \varepsilon \qquad (11)$$

where $X = X(X_1, X_2, ..., X_m)$ - the vector of independent (explaining) variables; β - the vector of parameters (to be determined); ε - a random error (deviation); Y - dependent (explained) variable. The theoretical linear multiple regression equation is

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_m X_m + \varepsilon \qquad (12)$$

where $\beta 0$ - the free term that determines the value of Y, in the case when all explanatory variables Xj are 0.

The empirical multiple regression equation can be represented as

$$Y = b_0 + b_1 X_1 + b_2 X_2 + ... + b_m X_m + e \qquad (13)$$

where b_0 , b_1, ..., b_m are estimates of the theoretical values of the β_0, β_1, β_2, ..., β_{m} regression coefficients (empirical regression coefficients); e - the deviation estimate of ε. When the assumptions of the least squares method (LSM) with respect to ε_i errors, estimates of the b_0, b_1, ..., b_m parameters of the β_0, β_1, β_2, ..., β_m parameters of the multiple linear regression are unbiased, efficient and consistent. LSM is used to estimate the parameters of the multiple regression equation.

According to the Fisher-Snedecor distribution tables, the critical value of the F - criterion (F_{tabl}) is found. To do this, set the level of significance α (usually it is taken equal to 0.05)

$$F_c = \frac{\sum (Y_{ic} - Y_{ac})^2}{m} \cdot \frac{n - m - 1}{\sum (y_i - Y_{ic})^2}, \qquad (14)$$

where Y_{ic} – the calculation value of the resulting model Y, mm Hg; Y_{ac} - average value of the of the resulting model Y; y_i - original value of y, mm Hg; m - the number of factors, pieces; n - the number of observations, pieces.

If the actual value $F_c > F_{tabl}$, then the coefficient of determination is statistically significant and the regression equation is statistically reliable.

Results and discussion. The safety of transportation of methane-air mixture (MAM) through the underground degassing system depends on mining-geological and mining-technical parameters. Consider the effect of the parameters of the MAM on the safety of the degassing system on the example of data ME "Sukhodolske-East".

According to the degassing standard, the transportation of the methane-air mixture is carried out through the degassing pipes laid through the mine workings and is carried out by creating a vacuum pump. Perform a calculation of the diameter of the pipeline and the choice of a vacuum pump for capturing methane-air mixture from underground boreholes. The design scheme of the underground pipeline 24 of the western sloping working face (WSW) is shown in Figure 1.

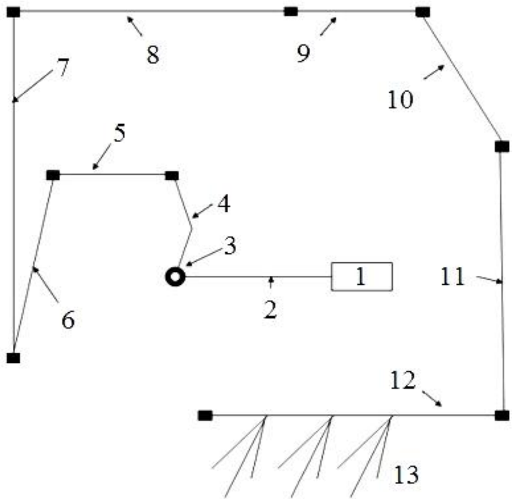

Figure 1 - Scheme of the underground pipeline 24 WSW: 1 - vacuum pump station; 2 - surface gas pipeline l = 50 m; 3 – borehole «1175» *l* = 915 m; 4 - degassing passage *l* = 30 m; 5 - air passage *l* = 70 m; 6 - air winze *l* = 40 m; 7 - conveyor incline *l* = 300 m; 8 - east main conveyor drift *l* =495 m; 9 - west conveyor drift *l* = 150 m; 10 - roadway with separate air ventilation *l* = 150 m; 11 - west flank air passage №23 *l* = 900 m; 12 - 24 west air drift *l* = 900 m; 13 – boreholes.

The initial data for the calculation are presented in Table 1.

Table 1 - The results of the calculation

Q_0, m^3/min	l_w, m	I_0, m^3/min	H, m	V_g, m^3	Q_g, m^3/s	Q_u, m^3/s	l_g, m	γ_c, kg/m^3	P_g, mm Hg	l_{gp}, m	d_d, m
38.1	4000	18.1	990	46.8	0.64	1.07	200	1.26	770	200	0.273

The results of the calculation will be presented in a Table 2.

Table 2 - The results of the calculation

Q_s, m^3/min	C_a, %	P_p, mm Hg	ΔP_u, (mm Hg)/m	d, m	d_i, m	ΔP_a, mm Hg	ΔP_m, mm Hg	P_i, mm Hg
52.63	43	798	0.1025	0.272	0.092	31.41	21.71	838.13

The pressure in the discharge nozzle of a vacuum pump can exceed atmospheric pressure by no more than 180 mm Hg:

$$P_i - P_b = 838.13 - 760 = 77.41 \le 180 \text{ mm Hg – condition performed}$$

In these conditions, we will study the changes in the parameters of the methane-air environment and their influence on the safety of the degassing system.

To do this, among the number of participating parameters (factors), it is necessary to select those that we can control. These include the following factors: the flow of the methane-air mixture, the length of the gas pipeline, the atmospheric pressure in the mine, the depth of the mining, the density of the methane-air mixture and the diameter of the pipeline that affects all of this.

Determine the degree of influence of factors methane-air mixture, which are taken into account when determining the optimal diameter of the pipeline (Table 3).

Table 3 - Factors affecting the diameter of the pipeline

№	$P_i - P_b$, mm Hg	Q_0, m^3/min	l_w, m	P_b, mm Hg	H, m	γ_c, kg/m^3	d, m
	y	x_1	x_2	x_3	x_4	x_5	x_6
1	62.46	47.1	4247	760	990	1.28	0.292
2	49.58	40	4000	755	950	1.27	0.277
3	67.9	50	4200	764	824	1.29	0.299
4	30.63	26	3700	762	550	1.26	0.235
5	20.23	15.1	2500	758	632	1.2	0.18
6	18.9	12	2356	758	458	1.1	0.165
7	15.79	5	2156	758	350	1.05	0.125
8	15.19	1.1	1980	760	300	1.4	0.089
9	15.09	1.1	1000	760	100	1.4	0.068
10	25.51	23	800	765	700	1.32	0.162
11	35.83	33	500	765	750	1.32	0.169
12	43.92	38	2400	770	824	1.26	0.244
13	59.03	47	2650	760	825	1.27	0.268
14	70.91	53	2950	760	840	1.27	0.286
15	83.93	59	3125	760	890	1.27	0.301
16	93.12	63	3400	760	900	1.26	0.314
17	95.87	64	3560	770	1000	1.26	0.318
18	103.47	67	3660	762	1050	1.26	0.325
19	106.29	68	3780	762	1090	1.26	0.329
20	117.21	72	3950	763	1120	1.26	0.339
21	159.18	85	4150	758	1250	1.29	0.364
22	169.04	88	4150	758	1250	1.29	0.364
23	122.98	73	4500	758	1300	1.29	0.344
24	122.98	88	6000	758	1300	1.29	0.344

When determining the multiple regression model the main task was to set a safety condition for the difference in pressure; therefore, some parameters varied independently of boundary conditions.

Determine the matrix of paired correlation coefficients, the number of observations 24 (Table 4).

If there is an inter-factor correlation coefficient in the matrix r_{XjXi}>0.7, then there is multicollinearity in this multiple regression model. In our case, $r_{X1\,X2}$, $r_{X1\,X4}$, $r_{X1\,X6}$, $r_{X2\,X4}$, $r_{X2\,X6}$, $r_{X4\,X6}$ have $|\ r\ |> 0.7$, which indicates the multicollinearity of the factors and the need to exclude one of them from further analysis.

Table 4 - Matrix of paired correlation coefficients

	Y	X_1	X_2	X_3	X_4	X_5	X_6
Y	1	0.960	0.716	-0.102	0.890	0.137	0.893
X_1	0.960	1	0.755	-0.005	0.952	0.127	0.959
X_2	0.716	0.755	1	-0.276	0.746	-0.069	0.822
X_3	-0.102	-0.005	-0.276	1	-0.020	0.178	-0.012
X_4	0.890	0.952	0.746	-0.020	1	0.072	0.941
X_5	0.137	0.127	-0.069	0.178	0.072	1	0.003
X_6	0.893	0.959	0.822	-0.012	0.941	0.003	1

Analysis of the first row of this matrix allows for the selection of factor signs that will be included in the model of multiple correlation dependence

$$Y = -4.732 + 1.621 \cdot X_1 .$$

Let's check by Fisher's criterion, according to which the calculated value, after selecting the factor, was 260.66 with m = 1 (since we have selected one factor). The tabular value of the Fisher criterion $F_{tabl} = 2.068658$ with $\alpha = 0.05$.

$F_c > F_{tabl}$, the coefficient of determination is statistically significant and the regression equation is statistically reliable.

For a visual assessment of the obtained regression model, we compare its values with the original values (Fig. 2).

As can be seen from Figure 2, the resulting model of value calculation corresponds to the original data of value original and is described with an accuracy of 95 %.

Conclusions. In determining the interrelation of the main influencing factors on the safety of methane-air mixture transportation, it has been established that the factor of consumption of methane-air mixture at the starting point of the gas pipeline has the maximum effect. As a result, a linear multiple regression of the form $Y = -4.732 + 1.621 \cdot X_1$ was obtained, allowing to establish the effect of the flow of methane-air mixture at the starting point of the gas pipeline (flow of borehole) on the safety of transportation of methane-air mixture.

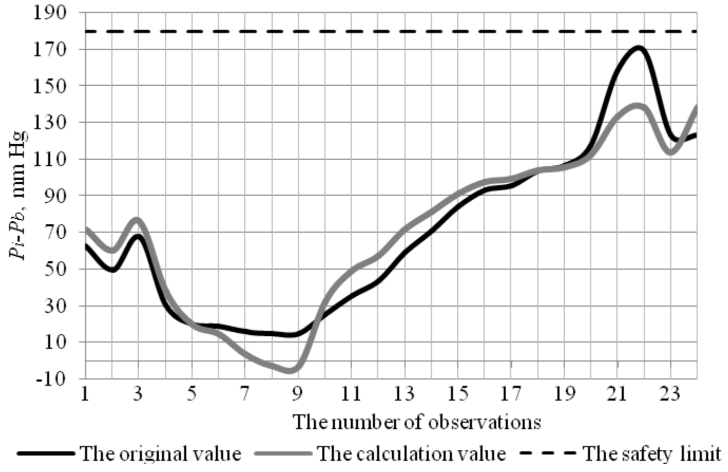

Figure 2 - Dynamics of changes in the pressure of the methane-air mixture of original and value calculation

The results make it possible to predict changes in the safety conditions of transportation of the methane-air mixture, and subsequently to manage them when changing the flow of methane from boreholes for the purpose of uninterrupted and trouble-free operation of the degassing system and the mine as a whole.

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Анотація. У статті відображені результати взаємозв'язку основних гірничо-геологічних і гірничотехнічних факторів, що впливають на безпеку транспортування метаноповітряної суміші при розробці вугільних родовищ.

Розглянуто вплив параметрів метано-повітряної суміші на безпеку системи дегазації на прикладі даних ШУ «Суходольська-Східна», де транспортування газової суміші здійснюється по дегазаційним трубам, що прокладені по гірничим виробкам і здійснюється за рахунок роботи вакуум-насоса. Розрахунки проводились згідно керівництву з проектування дегазації вугільних шахт, за яким визначено діаметр трубопроводу і вибір вакуум - насоса для каптажу метано-повітряної суміші з підземних свердловин. Встановлено взаємозв'язок між гірничотехнічними і гірничо-геологічними чинниками, що впливають на безпеку транспортування метаноповітряної суміші за допомогою регресійного аналізу. В аналізі враховувалися саме регульовані фактори. До них відносяться: витрата метаноповітряної суміші ділянки, довжина газопроводу виїмкової дільниці, атмосферний тиск у виробленні, глибина вироблення, щільність метано-повітряної суміші і діаметр трубопроводу.

При визначенні взаємозв'язку основних факторів, що впливають на безпеку транспортування метаноповітряної суміші встановлено, що максимальний вплив надає фактор витрати метаноповітряної суміші в початковій точці газопроводу. В результаті чого, отримана лінійна множинна регресія, яка дозволила встановити вплив витрати метаноповітряної суміші в початковій точці газопроводу на безпечні умови її транспортування. Отримана модель розрахунку значення гірничотехнічних і гірничо-геологічних факторів відповідає вихідним даним і описується з точністю до 95%.

Отримані результати дозволяють спрогнозувати зміни безпечних умов транспортування метаноповітряної суміші і надалі керувати ними при зміні витрати метану з свердловин з метою безперебійної та безаварійної роботи дегазаційного газопроводу.

Ключові слова: метановиділення, метаноповітряна суміш, діаметр газопроводу, гірничотехнічні і гірничо-геологічні чинники, розробка вугільних родовищ, регресійна модель.

Аннотация. В статье отображены результаты взаимосвязи основных горно-геологических и горнотехнических факторов, влияющих на безопасность транспортирования метановоздушной смеси при разработке угольных месторождений. Рассмотрено влияние параметров метановоздушной смеси на безопасность дегазационной системы на примере данных ШУ «Суходольское-Восточное», где транспортировка газовой смеси осуществляется по дегазационным трубам, проложенным по горным выработкам, и осуществляется за счет работы вакуум-насоса. Расчеты проводились согласно руководству по проектированию дегазации угольных шахт, по которому определен диаметр трубопровода и выбор вакуум – насоса для каптажа метановоздушной смеси с подземных скважин. Установлена взаимосвязь между горнотехническими и горно-геологическими факторами, влияющими на безопасность транспортирования метановоздушной смеси с помощью регрессионного анализа. В анализе учитывались именно регулируемые факторы. К ним относятся: расход метановоздушной смеси участка, длина газопровода выемочного участка, атмосферное давление в выработке, глубина выработки, плотность метановоздушной смеси и диаметр трубопровода. При определении взаимосвязи основных факторов влияющих на безопасность транспортирования метановоздушной смеси установлено, что максимальное воздействие оказывает фактор расхода метановоздушной смеси в начальной точке газопровода. В результате чего, получена линейная множественная регрессия, которая позволила установить влияние расхода метановоздушной смеси в начальной точке газопровода на безопасные условия ее транспортирования. Полученная модель расчета значения горнотехнических и горно-геологических факторов соответствует исходным данным и описывается с точностью до 95%. Полученные результаты позволяют спрогнозировать изменения безопасных условий транспортирования метановоздушной смеси и в дальнейшем управлять ими при изменении расхода метана из скважин с целью бесперебойной и безаварийной работы дегазационного газопровода.

Ключевые слова: метановыделение, метановоздушная смесь, диаметр газопровода, горнотехнические и горно-геологические факторы, разработка угольных месторождений, регрессионная модель.

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