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STATISTICAL ASSESSMENT OF THE INDICATOR YIELD OF VOLATILE MATTER FOR FORECASTING HAZARDOUS PROPERTIES OF COAL SEAMS

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СТАТИСТИЧНА ОЦІНКА ПОКАЗНИКА ВИХОДУ ЛЕТКИХ РЕЧОВИН ДЛЯ ПРОГНОЗУ НЕБЕЗПЕЧНИХ ВЛАСТИВОСТЕЙ ВУГІЛЬНИХ ПЛАСТІВ

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The article studies statistical models of the mass yield of volatile matter during the thermal decomposition of coals without air access with the aim (V^{daf}) with the aim of using this indicator to assess the degree of metamorphism (coalification) and forecast the hazardous properties of coal seams.

It is shown that the classification indicator of the yield of volatile matter, which is used in regulatory documents on the safe conduct of mining operations, is not sufficiently justified for these purposes. It was adopted in the absence of reliable knowledge about the structural and chemical composition of the organic part of the coal seam. The indicator V^{daf} characterizes the state of dry ash free organic (combustible) mass, and the composition of fossil coal, in addition, includes mineral impurities and moisture.

Purpose. To determine the probable relative errors in the measurement of absolute values indicator of the yield of volatile matter using statistical models. This will allow the indicator V^{daf} to be used with a given accuracy as the main classification criterion for the metamorphism (coalification) of coal seams to forecast their hazardous properties during mining operations.

The methodology is based on the use and statistical processing of experimental data from previous years, as well as on the formation of several sets of values V^{daf}, which have certain characteristic features. Further statistical analysis and assessment of these sets allows us to establish differences or similarities between statistical models of the criterion V^{daf}.

Results. It is shown that one of the significant factors of non-compliance with the normal law of distribution of the yield of volatile matter V^{daf}, as a random variable, is the different accuracy of its determination depending on the absolute values. The validity of using V^{daf} in engineering calculations of the forecast of hazardous properties of coal seams is proven only when its values are more than 15-20%.

For the first time, based on statistical models, ambiguous possible errors in determining the yield of volatile matter and the inexpediency of its use for forecasting are established. The need to use other indicators of the degree of metamorphism to improve the regulatory framework for safe mining operations, which directly reflect the content and properties of coal in the process of geological transformations, is proven.

Keywords: *coal seams, yield of volatile matter, measurement error, forecast, hazardous properties, mining operations, regulatory framework, improvement.*

Introduction. One of the main and most studied indicators of the degree of metamorphism is the yield of volatile matter during thermal decomposition of coals without access to air (V^{daf}). This indicator is currently one of the main classification parameters used to characterize the consumer properties of fossil coals [1] and forecast the hazardous properties of coal seams [2-5]. The hazardous and other negative properties of coal seams during mining operations include gas emission, occurrence of gas-dynamic phenomena (sudden outburst of coal and gas) and endogenous fires, increased dust formation and its tendency to explode. These and some other undesirable manifestations of hazardous properties of coal seams have a negative impact on technological processes and safety of mining operations, which often leads to accidents in underground conditions with catastrophic consequences. In this regard, a particularly urgent task is to carry out effective measures to ensure safe and accident-free mining operations. The health and lives of those working in underground conditions largely depend on the effectiveness of such measures developed in accordance with the regulatory framework [2-5]. Periodically occurring accidents in mines indicate the need for constant improvement of regulatory documents aimed at safe mining operations. In most cases, when forecasting the possibility of the manifestation of hazardous properties of a separate coal seam, the classification indicator V^{daf} is taken as constant within the entire mine field. In most cases, when forecasting the possibility of the manifestation of hazardous properties of an individual coal seam, the classification indicator V^{daf} is taken as constant within the entire mine field. This may lead to a decrease in the accuracy of the forecast and is associated with the possible heterogeneity of geological conditions within the mine field, which causes variations in the composition of coal seams. To date, the possible variation of the V^{daf} value within the boundaries of mine fields remains poorly understood. This may be due to the difficulties in collecting a sufficiently large sample of data for the entire mine area and the lack of detailed geological studies. This is confirmed by reference data from the "Catalogue of USSR Coal Seams by Dust Factor" [5], in which specific values are not indicated for 114 coal seams, but only the lower and upper limits of its change are given.

The objective. To study statistical models of V^{daf} and to establish within the limits of an individual coal seam the possible ranges of change of the classification indicator and the advisability of using its average values in the regulatory framework for forecasting the manifestation of hazardous properties of coal seams during mining operations.

The idea is to study the data on values V^{daf} for individual coal seams, given in reference (normative) and scientific and technical publications of previous years, which allows analyzing coal samples taken in different parts of the mine field. This makes it possible to consider randomly generated databases and study statistical models of the distribution of the classification indicator depending on statistical populations (data set). A statistical population includes a certain amount of data that have certain features (common properties) that are essential for their characterization.

Methods. Databases of sets V^{daf} with the following characteristics were preliminarily created:

1. Set of lower limits of change V^{daf}_{low} for 114 coal seams according to the "Catalogue of USSR coal seams by dust factor" [5].

2. Set of upper limits of change V^{daf}_{upp} for 114 coal seams [5].

3. Total set of 228 values of lower and upper limits of coal seams for which specific values V^{daf} are not specified [5].

4. Set of 206 data formed on the basis of information from different sources [6].

5. Set of values V^{daf} for 206 coal seams according to [5], information on which is given in [6].

6. Total set of 412 data formed according to data from [5] and [6].

7. Set of 2091 average values V^{daf} for coal seams from different coal deposits [5].

Research results. Before statistical processing of the material, the sets were subjected to grouping by variants in ascending order in ranked series. According to [7], with a sample size (n) less than one hundred, the number (k) of groups (intervals) is determined by the condition $k \le 5 \cdot \lg n$. The calculated values (k_{cal}) and those adopted in further calculations for the samples (k_{sam}) under consideration are given in Table 1. The calculated values k_{cal} were within 10.3÷16.6, and k_s was adopted as ten. In this case, the necessary requirement for statistical data processing is met [7].

The normal law of distribution (Gauss's law) plays an exceptional role in probability theory and mathematical statistics. The main feature of the Gaussian law is that it is a limiting law to which, under certain conditions, other known laws of distribution (log-normal, Weibull, gamma distribution, binomial, etc.) approach. The normal law of distribution is most often found in practice, so we will use it in our work.

To determine the optimal step size and interval in each sample (h_{cal}), the Sturges formula was used:

$$h_{cal} = \frac{V^{daf}_{max} - V^{daf}_{min}}{k_{sam}} = \frac{R}{k_{cal}}, \qquad (1)$$

where V^{daf}_{max} and V^{daf}_{min} are the maximum and minimum variants, respectively; R – range of variation, which represents the amplitude of oscillations, or the breadth of dispersion, and is a value dependent on random circumstances.

The calculated value h_{cal} for the considered samples was 3.1÷5.0%, and with the accepted value h_{cal}=10, the values h_{cal} were within 4.2÷5.3% (Table 1). An integer equal to five was taken as the interval unit in all samples.

Table 1

Results of the study of statistical models of the distribution of the yield of volatile matter during thermal decomposition of coals (V^{daf}) as a random variable

Set (Sample) number *	Sample (Set) values V^{daf}, %			Mode	Data set size	Indicators of mathematical statistics of distribution series								Skewness	Kurtosis	Pearson's criterion	
						Range V_{max} - V_{min}, %	number of intervals, pcs.		interval step, %		Dispersion	Standard deviation	Coefficient of variation				
	minimum	maximum	average				calculated	adopted	calculated	at k_s=10						critical value	samples
No	V_{min}^{daf}	V_{max}^{daf}	$\bar{V}_{sam}^{daf}$	M	n	R	k_{cal}	k_s	h_{cal}	h_s	D_s	σ_s	k_v	S	K	χ_{cr}^2	χ_s^2
1	1.3	49.0	16.3	2.5	114	47.7	10.3	10	4.6	4.8	192.8	13.9	85.1	0.58	-0.92	14.07	162.99
2	2.5	54.0	20.1	2.5	114	51.5	10.3	10	5.0	5.2	242.2	15.6	77.5	0.41	1.28	15.51	112.70
3	1.3	54.0	18.2	2.5	228	52.7	11.8	10	4.5	5.3	220.1	14.8	81.6	0.51	-1.08	15.51	256.77
4	1.4	45.9	24.5	27.5	206	44.5	11.6	10	3.8	4.5	100.9	10.0	40.9	-0.09	-0.45	14.07	10.39
5	2.3	44.2	25.0	22.5	206	41.9	11.6	10	3.6	4.2	107.0	10.3	41.4	-0.18	-0.68	14.07	16.69
6	1.4	45.9	24.8	25.0	412	44.5	13.1	10	3.4	4.5	103.7	10.2	41.1	-0.13	-0.58	14.07	25.03
7	1.3	52.1	25.7	37.5	2091	50.8	16.6	10	3.1	5.1	187.9	13.7	53.4	-0.21	29.2	15.51	618.52

Note to table *

1 – lower values V_{min}^{daf} according to [5];

2 – upper values V_{max}^{daf} according to [5];

3 – general interval series V_{min}^{daf}, V_{max}^{daf} according to [5];

4 – data according to source [6];

5 – data [5] corresponding to the coal seams specified in [6];

6 – common interval series for data from different sources [5, 6];

7 – processing of all data according to [5].

Sample characteristics of distributions (arithmetic mean) $\bar{V}_{sam}^{daf}$, dispersion D_s, standard deviation σ_s, coefficient of variation (k_v) are determined by the product method (conditional zero).

To approximately test the hypothesis of normal distribution of statistical populations (sets), we calculated skewness (S) and kurtosis (K) (Table 1). Also, Table 1 shows the results of calculating the parameters of statistical models for the distribution of the yield of volatile matter during thermal decomposition of coals as a random variable V_{min}^{daf}, V_{max}^{daf}, $\bar{V}_{sam}^{daf}$, n, R, D_s, σ_s and k_v.

To test the hypothesis about the normal distribution of statistical populations, we used the χ^2-Pearson criterion (Pearson's chi-squared test), based on a comparison of empirical (n) and theoretical (n_i') frequencies. It is a statistical test used to test hypotheses about the independence of categorical variables or the conformity of observed frequencies with theoretical expectations.

The calculated value of the Pearson criterion for each set was calculated according to the equation [6, 7]:

$$\chi_s^2 = \sum \frac{(n_i - n_i')^2}{n_i'} = \sum \frac{(O_i - E_i)^2}{E_i}, \quad (2)$$

where $E_i = n_i' = \dfrac{n \cdot h \cdot \varphi(z_i)}{\sigma_в}$ – theoretical (expected) frequencies for each interval; $z_i = \dfrac{V_i^{daf} - \bar{V}_s^{daf}}{\sigma_в}$; $\varphi(z_i) = \dfrac{1}{\sqrt{2\pi}} e^{-\frac{z_i^2}{2}}$ – Gaussian function; O_i – observed frequencies.

The critical value of Pearson's criteria and its calculated values for the considered data sets at a given level of significance α=0.05 are given in Table 1.

The results of the analysis of the considered populations showed (Table 1) that only the data [6-11] of set 4 correspond to the hypothesis of normal distribution. The distribution for this case can be considered almost symmetrical (S=-0.09), since it is less than 0.1. The kurtosis (excess) K=-0.45 is slightly different from zero, and given its negative value, the theoretical curve has a lower and “flatter” peak compared to the standard normal curve (Fig. 1). The calculated value of the Pearson criterion for the considered sample ($\chi_s^2 = 10.39$) is less than its critical value ($\chi_{cr}^2 = 14.07$) at the significance level (α=0.05) and the number of degrees of freedom equal to seven. The presented calculation results indicate that there is no reason to reject the hypothesis of normal distribution of a random variable from 206 variants according to data from different sources given in [6].

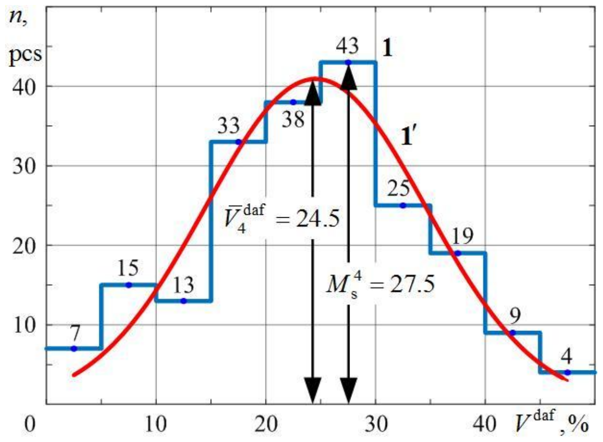


Fig. 1. Example of the histogram curve of the actualdistribution and the theoretical curve of the normal distribution of a random variable V^{daf} of the 4th data set of 206 variant [6]: 1 – the curve of the histogram of the distribution of the 4th set V^{daf} with a set size of 206 data; 1' – the theoretical curve of the normal distribution; $M_s^4 = 27{,}5$ – the mode for histogram 1; $\bar{V}_4^{daf} = 24{,}5$ – the average value of the yield of volatile matter in set 4 (Table 1) for calculating the theoretical curve 1' of the normal distribution

The 5th and 6th data sets of data, which were formed using experimental data [6], are also close enough to the normal distribution law for the calculated values of statistical parameters (S, K, χ_s^2). For these samples, the skewness (asymmetry) was in the range of -0.13 -0.18, the kurtosis (excess) in the interval -0.58 -0.68, and the Pearson criteria were 16.69 25.03, respectively (Table 1). This indicates that the values V^{daf} for these cases, in the first approximation, can also be considered as a random variable obeying the normal distribution law.

Such a conclusion cannot be made on the basis of statistical models in relation to variation series 1, 2, 3 and 7 (Table 1), obtained on the basis of data only from the “Catalogue...” [5]. None of the calculated statistical parameters of these sets (V^{daf}, M, D_s, σ_s, k_v, S, K, χ_s^2) even closely approaches the characteristics of a normal distribution in their value. For this reason, there is every reason to reject the hypothesis of a normal distribution V^{daf} as a random variable. Such a conclusion makes it possible to make an assumption about the existence of unidentified factors that significantly affect the formation of the 1st, 2nd, 3rd and 7th data sets on the basis of data from the “Catalogue...” [5]. Obviously, in order to obtain the values of the lower (V_{low}^{daf}) and upper (V_{upp}^{daf}) limits of the yield of volatile matter for a specific coal seam, coal samples were taken in different parts of the mine field. In this case, the absolute determinations for 114 coal seams and the formation of the 1st, 2nd, and 3rd data sets could have been influenced by the location of coal sampling sites in relation to the boundaries of the gas weathering zone and the distance to geological disturbances [6].

In the case under consideration, the data set (7) with a volume of 2091 variants is general for samples 1, 2 and 3. These sets are formed on the basis of the feature of the absence of specific values V^{daf} for 114 coal seams.

The statistical models of these data sets (1, 2, 3) should reflect the values of the parameters of the general set (7). In contrast, the statistical parameters of ranking series 1, 2, 3 differ significantly from data set 7 (Table 1). This is clearly illustrated by the graphs (Fig. 2 and 3) when comparing the histograms and theoretical curves of the normal distribution for sets of the 3rd and 7th populations. Between the histograms of the actual distributions 2 and 3, there are no, for the most part, unifying features. The mode $M_s^3 = 78$ was observed at a value $\bar{V}^{daf} = 2{,}5\%$ when considering the 228th option, and $M_s^7 = 288$ at $\bar{V}^{daf} = 37{,}5\%$ for the set size equal to the total amount of data (2091) of population 7.

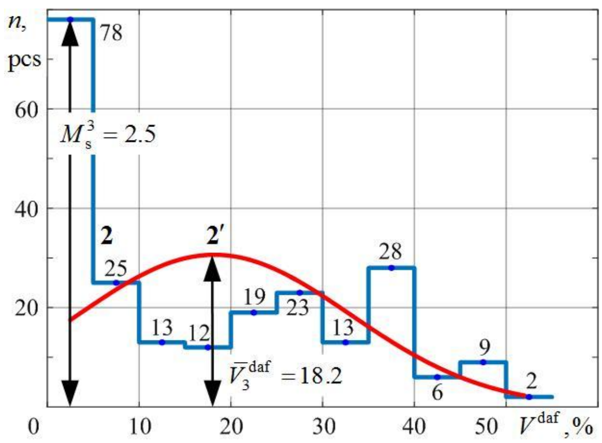


Fig. 2. Example of the histogram curve of the actual distribution and the theoretical curve of the normal distribution of a random variable V^{daf} of the 3th data set of 228 variant [5]: 2 – the curve of the histogram of the distribution of the 3th set V^{daf} with a set size of 228 data; 2' – the theoretical curve of the normal distribution; $M_s^3 = 2.5$ – the mode for histogram 2; $\bar{V}_3^{daf} = 18.2$ – the average value of the yield of volatile matter in set 3 (Table 1) for calculating the theoretical curve 2' of the normal distribution

In the first case, 34.2% of the data from the total number (228) in the considered set fell within the range of $V_i^{daf} = 0 \div 5.0\%$. In the second case, only 13.7% of the data from the total number (2091) fell within this range. This indicates that in most cases, the coal seams for which the lower and upper limits of possible values V^{daf} are indicated are characterized by lower values V^{daf}.

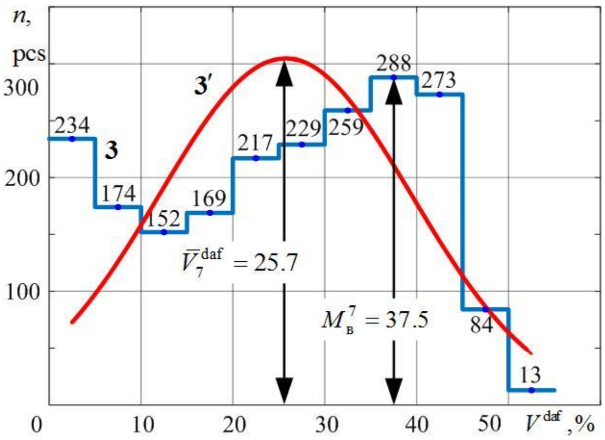


Fig. 3. Example of the histogram curve of the actual distribution and the theoretical curve of the normal distribution of a random variable V^{daf} of the 7th data set of 2091 variant: 3 – the curve of the histogram of the distribution of the 7th set V^{daf} with a set size of 2091 data; 3' – the theoretical curve of the normal distribution; $M_s^7 = 35.7$ – the mode for histogram 2; $\bar{V}_7^{daf} = 25.7$ – the average value of the yield of volatile matter in set 7 (Table 1) for calculating the theoretical curve 3' of the normal distribution

This is confirmed by the ratio of average values, where $\bar{V}_3^{daf} = 18.2\% < \bar{V}_7^{daf} = 25.7\%$. The difference between the sets of distribution series 3 and 7 also lies in the different ratio between the modes and average values of the samples. For set 3, the mode $M_s^3 = 2.5$ is and it is significantly smaller $\bar{V}_3^{daf} = 18.2\%$. The ratio of these parameters for set 7 is of the opposite nature $M_s^7 = 37.5\% > \bar{V}_7^{daf} = 25.7\%$. Sets 1, 2 differ from the general set 7 by approximately the same features (Table 1). Parameters close in their values to the indicators of normal distribution were established for sets 4, 5, 6. Their main distinguishing feature was the use of information of the yield of volatile matter publication [6] published in different periods of time for each coal seam. This practically excluded the possibility of analyzing coal samples taken in close places of the coal seam and introduced a certain element of randomness into the determination of the values of the classification indicator. This is confirmed by the proximity of the distribution of variants 4, 5 and 6 sets to the normal law (Table 1, Fig. 1).

To establish possible reasons for the discrepancy between the 1st, 2nd, 3rd and 7th sets and the normal distribution law, we examined in more detail the parameters characterizing their variation series. In particular, we examined changes in relative frequencies (Δ_i) in individual intervals:

$$\Delta_i = \frac{n_i}{n} \cdot 100, \%, \quad (3)$$

where n_i – number of variants in the interval, pcs; n – total volume of the set under consideration, pcs.

The results of calculating the values Δ_i are summarized in Table 2. The graphs of their changes (Fig. 4) indicate some patterns common to the 1st, 2nd, 3rd and 7th sets. They consist of an unambiguous decrease in relative frequencies for all sets in the range of change V^{daf} from zero to 10-15%. Then the values Δ_i increase monotonically and synchronously for all series, reaching maximum values (11.4–13.7%) at V^{daf} = 37.5%. This value V^{daf} is the mode for the 7th set. With further increase V^{daf}, the relative frequencies in the intervals decrease for all sets under consideration.

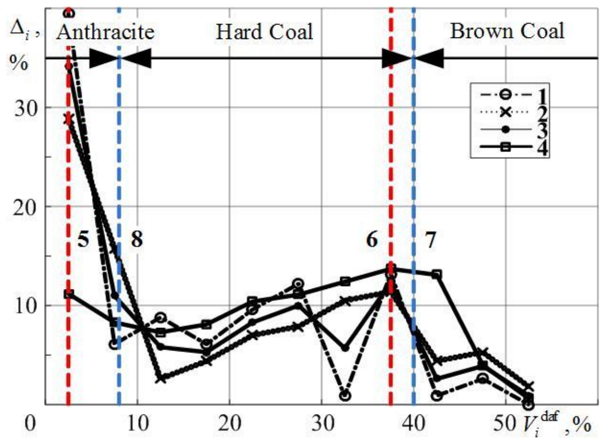


Fig. 4. Distribution of relative frequencies Δ_i of the yield of volatile matter release in individual intervals:
1, 2, 3, 4 – distribution curves for the 1st, 2nd, 3rd and 7th sets, respectively;5, 6 – mode values for the 1st, 2nd, 3rd and 7th sets, respectively; 7, 8 - boundary values V^{daf} that separate, according to [1], brown and hard coals, hard coals and anthracites, respectively

Table 2

Information on the values of relative frequencies (Δ_i) in individual intervals of variation rows for the 1st, 2nd, 3rd and 7th sets of the yield of volatile matter (V^{daf})

Set number	Absolute (n_i) and relative (Δ_i) frequencies	Intervals V_i^{daf}, %										
		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55
1	n_i, pcs	45	7	10	7	11	14	1	15	1	3	–
	Δ_i^1, %	39.5	6.1	8.8	6.1	9.6	12.2	0.9	13.2	0.9	2.6	–
2	n_i, pcs	33	18	3	5	8	9	12	3	5	6	2
	Δ_i^2, %	28.9	15.8	2.6	4.4	7.0	7.9	10.5	11.4	4.4	5.3	1.8
3	n_i, pcs	78	25	13	12	19	23	13	28	6	9	2
	Δ_i^3, %	34.2	11.0	5.8	5.3	8.3	10.0	5.7	12.3	2.6	3.9	0.9
7	n_i, pcs	234	174	152	169	217	229	259	287	273	84	13
	Δ_i^7, %	11.2	8.3	7.3	8.1	10.4	11.1	12.4	13.7	13.1	4.0	0.6

The unambiguous direction and synchronicity of the change Δ_i in individual ranges V^{daf} for all the sets under consideration indicate the presence of a certain pattern of decreasing the proportion of randomness with a sufficient sample size. The need to comply with the condition of a sufficient number of observations is the deviation from the general pattern of the value Δ_i in the interval V^{daf} = 30÷35% for the 1st set. The total number of ranked variants (n) was 114, and in the interval the value n_i was equal to one case. Such a deviation from the general pattern was eliminated when considering the 3rd set with n = 228 and n_i = 13, which is clearly seen from the graph (Fig. 4).

The established patterns of distribution of coal seams by the value of the classification indicator of the yield of volatile matter (V^{daf}) are not taken into account in the regulatory documents [2-5] governing the safety of mining operations. Thus, the share of coal seams for which specific values V^{daf} have not been established [5] accounts for more than half of the cases with a yield of volatile matter of less than 15%. The mode (maximum number of cases) occurs for the 1st, 2nd, and 3rd sets at V^{daf} = 0÷5%. In this case, it can be naturally concluded that in most cases specific values V^{daf} (less than 8%) have not been established for coal seams containing anthracites. This indicates existing shortcomings in establishing the hazardous properties of anthracite coal seams when using the yield of volatile matter as the main classification indicator for the entire series of degrees of metamorphism (coalification) of fossil coals.

The features of the change V^{daf} in the ranking series are taken into account when developing the industrial classification [1] for establishing the consumer properties of coals. When determining coal grades V^{daf}, is not used as a classification indicator for values less than 8 and more than 40%. For V^{daf} < 8%, coals are classified as anthracites, and instead of V^{daf}, the volumetric yield of volatile matter (V_V^{daf}) is used as a classification indicator. For V^{daf} > 40%, coals are classified as brown, and the maximum moisture capacity (W_{max}^{af}) is used as a classification indicator. As a classification indicator V^{daf} in the industrial classification [1] is used with its values from 8 to 40%. Such a range V^{daf} is characterized by a one-sided and monotonous increase in the relative frequency (Δ_i) for the 1st, 2nd, 3rd and 7th sets (Fig. 4). The maximum relative frequency (Δ_i = 13.7%) of the general set 7, practically the general one, corresponds to $\bar{V}_i^{daf} = 37.5\%$. Such a value V^{daf} differs little from the upper limit of the use of this indicator in the industrial classification [1].

The presented results show that in the considered range of change V^{daf} (8.0÷40.0%), the relative frequencies (Δ_i) of the 1st, 2nd, and 3rd sets change synchronously with the relative frequency in the intervals of the conditionally general set 7. This confirms the reliability V^{daf} of its change in this range as a classification indicator, including for forecasting the hazardous properties of coal seams. The relationship between relative frequencies ($\Delta_i^1, \Delta_i^2, \Delta_i^3$) with Δ_i^7 is characterized by the correlation coefficient r = 0.77, with values V^{daf} changing from 10 to 40%. Such closeness of the correlation dependence between the relative frequencies of samples of the 1st, 2nd and 3rd sets from Δ_i^7 is not observed at V^{daf} < 8% and V^{daf} > 40% (r = 0.46), which confirms the validity of using other classification indicators in industrial classification [1] instead of the weight yield of volatile matter.

In this connection, doubts arise about the reliability and accuracy of the forecast of hazardous properties of coal seams according to [2-5], when values V^{daf} of less than 8 and more than 40 percent are used. From logical reasoning it follows that the maximum errors in determination are possible in the case of considering the 1st and 2nd sets. Each of them is respectively represented by 114 variants of the lower ($V_{\text{low}}^{\text{daf}}$) and upper ($V_{\text{upp}}^{\text{daf}}$) values of the yield of volatile matter for a specific coal seam. A close (r = 0.99) correlation relationship has been established between $V_{\text{low}}^{\text{daf}}$ and $V_{\text{upp}}^{\text{daf}}$ (Fig. 5) [8].

Deviations of the averaging lines from the bisector of the coordinate grid are on average about ±1.5÷2%, which indicates the stability of the values of the lower and upper limits V^{daf} for the separately considered coal seam. Based on the values of the regression coefficients of equations 1 and 2 (Fig. 5) [8], the average difference between the lower and upper values V^{daf} for the seams under consideration is about 25%, which does not guarantee high accuracy of the forecast of the manifestation of hazardous properties of coal seams during mining operations.

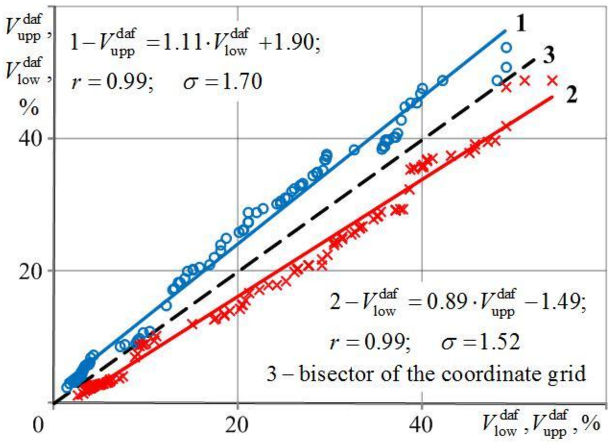


Fig. 5. The relationship between the upper ($V_{\text{upp}}^{\text{daf}}$, set 2) and lower ($V_{\text{low}}^{\text{daf}}$, set 1) values of the yield of volatile matter from coal seams for which specific values of the indicator are not specified [5], [6, 8]: ×, ○ – experimental data;
1, 2 – averaging lines for dependencies $V_{\text{upp}}^{\text{daf}} = f\left(V_{\text{low}}^{\text{daf}}\right)$ and $V_{\text{low}}^{\text{daf}} = f\left(V_{\text{upp}}^{\text{daf}}\right)$, respectively;
3 – bisector of the coordinate grid;
r – correlation coefficients; σ – standard deviations

Changes in the values of $V_{\text{low}}^{\text{daf}}$ and $V_{\text{upp}}^{\text{daf}}$ were also considered depending on the average values of the yield of volatile matter index ($\bar{V}^{\text{daf}}$) for the 1st and 2nd sets (Fig. 6) [8].

The regression coefficients of equations 1 and 2 are 0.94 and 1.06, respectively. Their values show that the difference between the average lower and upper values V^{daf} (lines 1 and 2) within one coal seam is slightly more than 10 percent. The results of the joint statistical processing of the lower ($V_{\text{low}}^{\text{daf}}$) and upper ($V_{\text{upp}}^{\text{daf}}$) limits of the change in the yield of volatile matter of sets 1 and 2 from their average values $\bar{V}^{\text{daf}}$ (228 pairs of data) established a high (r = 0.99) correlation direct proportional dependence (line 3) within the boundaries of the coal seams under consideration.

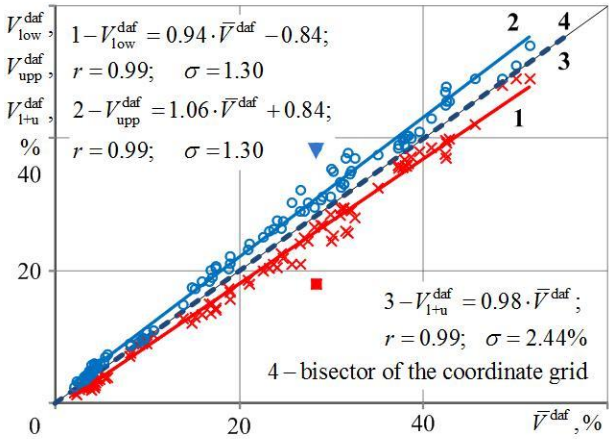


Fig. 6. Dependence of the lower ($V_{\text{low}}^{\text{daf}}$) and upper ($V_{\text{upp}}^{\text{daf}}$) limits of change in the yield of volatile matter on their average value within the boundaries of one coal seam [5], [6, 8]:
×, ○ – experimental data on the lower and upper limits of change, respectively, within the boundaries of one mine field;
▼, ■ – respectively, the lower (18.3%) and upper (38.6%) limits of change V^{daf} for coal seams k_{12} Verkhnyaya Marianna of the Kostenko mine;
1, 2 – averaging lines of the lower and upper limits, respectively; 4 – bisector of the coordinate grid;
r – correlation coefficients; σ – standard deviations

Straight line 3 practically coincided with the bisector (4) of the coordinate grid, which indicates the stability and constancy of the indicator V^{daf} for the considered sample of coal seams. The only exception is the data for the seam k_{12} Verkhnyaya Marianna of the Kostenko mine, for which $V_{\text{low}}^{\text{daf}} = 18.0\%$ and $V_{\text{upp}}^{\text{daf}} = 38.6\%$ (Fig. 6). The reasons for such a discrepancy in the values V^{daf} have not been established and additional consideration is required.

It can be assumed that for cases of unambiguous determination V^{daf} according to [5] within one mine field, the given value of the classification indicator reflects its average parameters for the conditions under consideration. The share of coal seams with unambiguously specified values V^{daf} [5] is about 95% of their total number (2091). With such a ratio of the considered coal seams in the conditionally general 7th set, the variants of set 5 (Table 1), without a large error, can be considered as average indicators for individual coal seams. This gives grounds to consider the randomly formed variants of set 4 [6] depending on the expected average values V^{daf} given for these coal seams in the normative document [5]. A high correlation (r = 0.94) has been established between the values V_1^{daf} of the yield of volatile matter given in the "Catalog..." [5] and V_2^{daf} from other sources of information given in [6] (Fig. 7) [8].

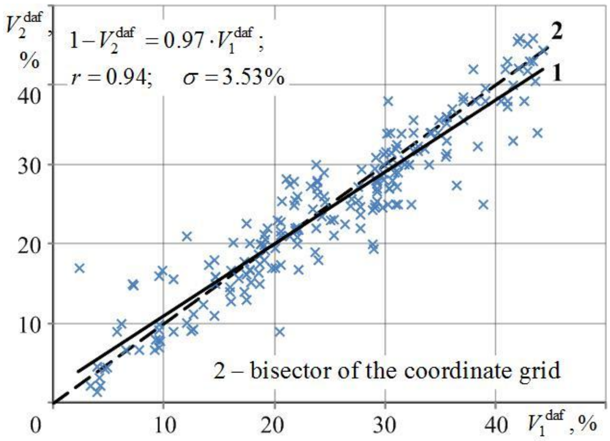


Fig. 7. Dependence of the correspondence of the yield of volatile matter during thermal decomposition of coals from different coal deposits between the data V_1^{daf} of the catalogue [5] and V_2^{daf} according to other sources of information [6]:
× – points determining the relationship between V_1^{daf} and V_2^{daf}; 1 – straight line obtained from the results of processing experimental data;
2 – bisector of the coordinate grid;
r – correlation coefficients; σ – standard deviations

The results obtained from statistical processing of data from other sources of information [6] are practically no different from the established values of the parameters when processing data [5] for coal seams, with unambiguously established values of V^{daf} (Fig. 6).

When processing the variant from different sets (1, 2) and (4), practically coinciding equations 3 (Fig. 6) and 1 (Fig. 7) were obtained. This additionally indicates the relative constancy of the V^{daf} index for different coal seams in different coal basins. The obtained averaging straight lines 3 (Fig. 6) and 1 (Fig. 7) deviate insignificantly from the bisectors of the coordinate grids. Along with this, there is a significant number of individual values V^{daf} that noticeably deviate from straight lines (1, 3) Fig. 7 and 6. In addition to the distance from the sampling site to the boundaries of gas weathering zones and geological disturbances [6, 8], other, fairly significant factors could have influenced the deviations of experimental data from the averaging straight lines. This is evidenced by the discrepancy between the data [5] and the normal distribution law (Fig. 2). One of the main reasons for such discrepancy is the grouping of a significant number of coal seams (45.1%), for which specific V^{daf} values are not specified, in a narrow range of its variation from 0 to 10%. The share of the remaining coal seams (54.9%), with V^{daf} changing in a wider range from 10 to 54%, accounts for the remaining number of variants. This indicates that one of the significant factors of discrepancy with the normal distribution law of V^{daf}, as a random variable, may be the different accuracy of its determination depending on the absolute values.

To assess the influence of this factor, we examined the absolute (σ_i) and relative ($\Delta\sigma_i$) standard deviations from the averaging lines in individual ranges of change in the values of the yield of volatile matter (Table 3) [8].

The variants of sets 3 and 4 (Table 1) accepted for statistical processing were formed according to different characteristics. Set 3 contains data on coal seams [5] for which specific V^{daf} values have not been established. It turned out that anthracite and semi-anthracite coal seams quantitatively predominate in it, since more than half of the total number of coal seams under consideration fell into the distribution intervals with a yield of volatile matter of less than 15%. Set 3 was formed from other sources of information based on data [6], which were published in different years. This predetermined the element of chance, and therefore, the proximity to the normal distribution law (curve 1, Fig. 1).

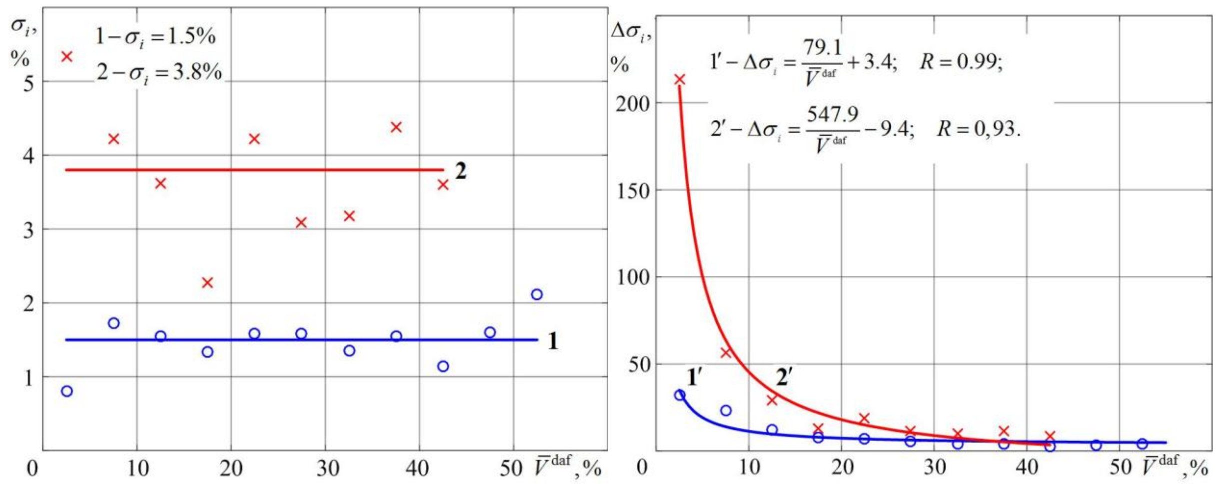
Despite the distinctive features of sets 3 (V_{l+u}^{daf}) and 4 (V_2^{daf}), when statistically processed depending on the values $\bar{V}^{daf}$ and V_1^{daf} according to [5], practically identical equations were obtained to describe line 3 (Fig. 6) and line 1 (Fig. 7) (Table 3). The regression coefficients of these equations, 0.98 and 0.97, respectively, differ from each other by one percent.

The absolute (σ_i) and relative ($\Delta\sigma_i$) standard deviations of individual values V^{daf} from the averaging lines differed more significantly (Table 3). In the intervals of change $\bar{V}^{daf}$ of the value $\bar{\sigma}_i$ and $\Delta\sigma_i$ of set 4 in all cases exceeded these indicators for set 3. The maximum excess of 6.7 times was in the interval V^{daf} of change from 0 to 5 percent. In the remaining intervals, the parameters differed from each other by 2-3 times. Quantitative differences between σ_i and $\Delta\sigma_i$ for sets 3 and 4 are clearly illustrated by the graphs (Fig. 8). The absolute values σ_i for both sets changed insignificantly in the intervals, their average values for the 3rd and 4th sets were 1.5 and 3.8%, respectively (Fig. 8, a). Relative standard deviations $\Delta\sigma_i$ in both cases tended to decrease with an increase $\bar{V}_i^{daf}$ (Fig. 8, b).

Table 3

Information on absolute (σ_i) and relative ($\Delta\sigma_i$) values of standard deviations from averaging lines in individual intervals of change in the yield of volatile matter (V^{daf})

Set number and amount of data	Standard deviation from the averaging line	Variation ranges V^{daf} and average values $\bar{V}_i^{daf}$, %										
		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55
		2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5
straight line 3 (Fig. 6), $V_{1+u}^{daf} = 0.98 \cdot \bar{V}^{daf}$												
№ 3, 228	$\bar{\sigma}_i$, %	0.80	1.73	1.54	1.34	1.59	1.58	1.36	1.54	1.15	1.60	2.12
	$\Delta\sigma_i = \frac{\bar{\sigma}_i}{\bar{V}_i^{daf}} \times$ ×100, %	32.0	23.1	12.3	7.7	7.1	5.7	4.2	4.1	2.7	3.4	4.0
straight line 1 (Fig.7), $V_2^{daf} = 0.97 \cdot V_1^{daf}$												
№ 4, 206	$\bar{\sigma}_i$, %	5.33	4.23	3.62	2.28	4.22	3.08	3.17	4.38	3.61	–	–
	$\Delta\sigma_i = \frac{\bar{\sigma}_i}{\bar{V}_i^{daf}} \times$ ×100, %	213.1	56.4	28.9	13.1	18.7	11.2	9.8	11.7	8.5	–	–



a b

Fig. 8. Dependence of the change in absolute (a) and relative (b) standard deviations of the yield of volatile matter on the averaging lines (3 and 1, Table 3) for the 3rd and 4th sets:
×, ○ – experimental values for the 3rd and 4th sets, respectively; 1, 2 – line segments corresponding to the average values of absolute standard deviations ($\bar{\sigma}_i$) for the 3rd (1.5%) and 4th (3.8%) sets; 1', 2' – averaging curves (hyperbola) of relative standard deviations ($\Delta\sigma_i$) for the 3rd and 4th sets, respectively; R – correlation ratio

At first glance, the absolute deviations from the averaging lines obtained for both sets are acceptable for engineering calculations. However, changes $\Delta\sigma_i$ in individual intervals $\bar{V}_i^{daf}$ refute such conclusions. In the interval V^{daf} from 0 to 5 percent, the relative errors of the 3rd and 4th sets were 32.0 and 213.1%, respectively (Table 3, Fig. 8, b).

Stabilization of relative errors within the limits acceptable for engineering calculations (up to 10%) for the considered sets is observed at $V^{daf} > 20\%$ (Fig. 8, b). This indicates that the use $V^{daf} < 20\%$ of hazardous properties of coal seams in regulatory documents [2-5] for forecasting can lead to significant errors. This is evidenced by the coinciding nature of the changes in $\bar{\sigma}_i$ and $\Delta\sigma_i$ and their close values for two sets formed according to different characteristics. According to the obtained results of comparing $\bar{\sigma}_i$ and $\Delta\sigma_i$ for two sets, it follows that the permissible error of less 10% in determining V^{daf} can only be achieved for values of this indicator greater than 20%.

In addition to the location of coal sampling in the mine field and the absolute value of V^{daf}, the error in its determination is also affected by ash content [6, 8].

As the ash content increases, the proportion of volatile matter from mineral components increases and the proportion of organic mass decreases, to which the total amount of volatile matter from the organic and mineral parts of coals refers when recalculated to dry ash-free mass. Due to the lack of methods for complete demineralization of the sample, it is impossible to obtain an accurate V^{daf} in the laboratory, and recalculation of volatile matter to organic mass leads to an overestimation of the indicator. The indicator V^{daf} only approximately characterizes the behavior of the organic mass of coals during thermal destruction and is completely unacceptable for calculations with high ash content of samples. In accordance with the current situation, when establishing the consumer properties of hard coals, their ash content should not exceed 10% [6, 8]. Samples with higher ash content are pre-enriched in organic or inorganic liquids according to developed standard methods. Such an artificial reduction in the content of mineral impurities in coal samples during determination V^{daf} does not correspond to the natural state of coal seams, which undoubtedly affects the accuracy of forecasting their hazardous properties.

Conclusions. The conducted studies of the statistical assessment of the mass yield of volatile matter during the thermal decomposition of coals without air access with the aim of using this indicator to assess the degree of metamorphism (coalification) and forecast the hazardous properties of coal seams allowed us to draw the following conclusions:

- the hypothesis about the normality of the distribution of the mass yield of volatile matter (V^{daf}) for the set of coal seams of different coal deposits from 2091 variants was not confirmed;
- individual sets of samples from the general set have the same nature of distribution of relative frequencies: with an increase in V^{daf} to 10% they decrease; in the range of V^{daf} from 10 to 40% they increase; at values V^{daf} >40% – there is a decrease again;
- based on statistical data processing and close correlation dependencies, the validity of using V^{daf} it in the range of its change of 8-40% as a classification indicator for establishing the consumer properties of coals has been proven;
- based on individual values, the average difference between the lower and upper limits V^{daf} is about 25%, which does not guarantee high accuracy in forecasting the manifestation of hazardous properties of mine seams during mining operations;
- difference between the regression coefficients of the averaged straight lines for the lower and upper limits of change V^{daf} is about 5%, a high (r = 0.99) correlation direct proportionality was established between the lower and upper limits of change V^{daf} within the boundaries of the considered coal seams. The exception was the data for one seam k_{12} from the totality of 228 pairs of considered variants;
- the share of coal seams with single-digit indicated values is about 95% of their total number of 2091 considered. This determined the high correlation (r = 0.94) between the values V^{daf} given in different sources of information;
- the distance from the coal sampling site to the boundaries of gas weathering zones and geological disturbances is not the only factor influencing the deviations of experimental data from the averaging lines;
- one of the significant factors of non-compliance with the normal distribution law V^{daf}, as a random variable, is the different accuracy of determining this indicator in individual ranges of its absolute values;
- the most significant relative deviations $\Delta\sigma$ (more than 200%) are possible at values $\bar{V}^{daf} < 15\%$;
- acceptable relative errors, permissible for engineering calculations, can be guaranteed only for absolute values V^{daf} greater than 20%;
- due to the lack of methods for complete demineralization of coal samples, it is impossible to obtain an exact V^{daf} value in the laboratory. The indicator V^{daf} only approximately characterizes the behavior of the organic mass of coals during thermal destruction and is unacceptable for calculations with high ash content of samples.

References

1. ДСТУ 3472:2015 Вугілля буре, кам’яне та антрацит. Класифікація. Київ: ДП «УкрНДНЦ». 2016. 8 с.
2. СОУ 10.1.00174088.011-2005. Правила ведення гірничих робіт на пластах, схильних до газодинамічних явищ. [Чинний від 2005-12-01]. Вид. офіц. Київ: Мінвуглепром України, 2005. 224 с.
3. Руководство по проектированию вентиляции угольных шахт. Киев: Основа, 1994. 311 с.
4. КД 12.01.402-2000. Руководство по предупреждению и тушению эндогенных пожаров на угольных шахтах Украины. [Чинний від 2000-12-18]. Вид. офіц. Донецьк: Мінтопенерго України, 2000. 216 с.
5. Руководство по борьбе с пылью в угольных шахтах. Москва: Недра,1979. 319 с.

6. Антощенко М.І., Руднєв Є.С., Філатьєв М.В., Філатьєва Е.М. Статистичні моделі класифікаційного показника ступеня метаморфізму вугілля для прогнозу небезпечних властивостей шахтопластів. Вісті Донецького гірничого інституту. №1 (48). 2021. С. 49-63.
7. Albright B. Essentials of Mathematical Statistics. Jones & Bartlett Learning; 1st edition, 2013. 598 p.
8. Руднєв Є.С. Розвиток наукових основ прогнозу небезпечних властивостей шахтопластів за ступенем вуглефікації : автореф. дис. … д-ра техн. наук : 05.26.01. Дніпро, 2023. 40 с.

R e f e r e n c e s

1. DSTU 3472:2015 Vughillja bure, kam'jane ta antracyt. Klasyfikacija. Kyiv: DP «UkrNDNC». 2016. 8 s.
2. SOU 10.1.00174088.011-2005. Pravyla vedennja ghirnychykh robit na plastakh, skhyljnykh do ghazodynamichnykh javyshh. [Chynnyj vid 2005-12-01]. Vyd. ofic. Kyiv: Minvughleprom Ukrajiny, 2005. 224 s.
3. Rukovodstvo po proektirovaniju ventiljacii ugol'nyh shaht. Kyiv: Osnova, 1994. 311 s.
4. KD 12.01.402-2000. Rukovodstvo po preduprezhdeniju i tusheniju jendogennyh pozharov na ugol'nyh shahtah Ukrainy. [Chynnyi vid 2000-12-18]. Vyd. ofits. Donetsk: Mintopenerho Ukrainy, 2000. 216 s.
5. Rukovodstvo po bor'be s pyl'ju v ugol'nyh shahtah. Moskva: Nedra,1979. 319 s.
6. Antoshchenko M.I., Rudniev Ye.S., Filatiev M.V., Filatieva E.M. Statystychni modeli klasyfikatsiinoho pokaznyka stupenia metamorfizmu vuhillia dlia prohnozu nebezpechnykh vlastyvostei shakhtoplastiv. Visti Donetskoho hirnychoho instytutu. №1 (48). 2021. S. 49-63.
7. Albright B. Essentials of Mathematical Statistics. Jones & Bartlett Learning; 1st edition, 2013. 598 p.
8. Rudniev Ye.S. Rozvytok naukovykh osnov prohnozu nebezpechnykh vlastyvostei shakhtoplastiv za stupenem vuhlefikatsii : avtoref. dys. … d-ra tekhn. nauk : 05.26.01. Dnipro, 2023. 40 s.

Руднєв Є. С. Статистична оцінка показника виходу летких речовин для прогнозу небезпечних властивостей вугільних пластів

У статті проведено дослідження статичних моделей масового виходу летких речовин при термічному розкладанні вугілля без доступу повітря (V^{daf}*) з метою застосування цього показника для оцінки ступеня метаморфізму (вуглефікації) та прогнозу небезпечних властивостей шахтопластів.*

Показано, що класифікаційний показник виходу летких речовин, який використовується у нормативних документах з безпечного ведення гірничих робіт не є достатньо обснованим для цих цілей. Він був прийнятий за відсутності достовірних знань про структурно-хімічний склад органічної частини вугільного пласта. Показник V^{daf} *характеризує стан сухої беззольної органічної (горючої) маси, а до складу викопного вугілля, крім цього входять мінеральні домішки та волога.*

Мета. Визначити ймовірні відносні похибки вимірювання абсолютних значень показника виходу летких речовин, використовуючи статистичні моделі. Це дозволить із заданою точністю застосовувати показник V^{daf} *як основний класифікаційний критерій метаморфізму (вуглефікації) вугільних пластів для прогнозу їх небезпечних властивостей під час гірничих робіт.*

Методика базується на використанні та статистичній обробці експериментальних даних минулих років, а також на формуванні кількох сукупностей значень V^{daf}*, які мають певні характерні ознаки. Подальший статистичний аналіз та оцінка цих сукупностей дозволяє встановити відмінності або подібності між статистичними моделями критерію* V^{daf}*.*

Результати. Показано, що одним з істотних факторів невідповідності нормальному закону розподілу виходу летких речовин V^{daf}*, як випадкової величини, є різна точність її визначення в залежності від абсолютних значень. Доведено обґрунтованість використання* V^{daf} *у інженерних розрахунках прогнозу небезпечних властивостей шахтопластів тільки при його значеннях більше 15-20%. Вперше на основі статистичних моделей встановленні неоднозначні можливі похибки визначення виходу летких речовин і недоцільність його застосування для прогнозу. Доказана необхідність застосування інших показників ступеня метаморфізму для удосконалення нормативної бази з безпечного ведення гірничих робіт, які безпосередньо відображають вміст й властивості вугілля в процесі геологічних перетворень.*

Ключові слова: *вугільні пласти, вихід летких речовин, похибка вимірювання, прогноз, небезпечні властивості, гірничі роботи, нормативна база, удосконалення.*

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