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ON THE DEPENDENCE OF THE GAS CAPACITY OF FOSSIL COALS ON THE DEGREE OF METAMORPHIC TRANSFORMATION OF COAL SEAMS

Rudniev Ye.

Volodymyr Dahl East Ukrainian National University

Abstract. Purpose: To determine the correlation strength between the sorption methane capacity of hard (bituminous) coals and anthracites and the degree of metamorphic transformation of coal seams with changes in pressure and temperature conditions.

Methodology: The research methodology involves statistical processing by the least squares method of the experimentally established values of the methane capacity (*a*) of hard (bituminous) coals and anthracites, from the indicator of the yield of volatile matter during thermal decomposition of coals without air access (V^{daf}). The values of pressure (*P*) during laboratory experiments and temperature (*t*), corresponding to the depth of occurrence of coal seams, are considered as additional influencing factors.

Results. When changing the pressure in the range from 0.1 MPa to 5.0 MPa, a high correlation dependence of the sorption methane capacity of hard coals and anthracites (*a*) on the yield of volatile matter was obtained in all cases. High pressure (5 MPa and more) causes not only an increase in the standard deviations from the averaging curves, but also leads to a change in the type (character) of the dependence of the sorption methane capacity on the yield of volatile matter. At atmospheric pressure (*P*=0.1 MPa), with an increase in the degree of metamorphic processes (further decrease in the V^{daf} values), only a one-sided increase in the sorption methane capacity of fossil coals is observed. The sigmoid more reliably reflects the one-sided nature of the change in the sorption methane capacity of hard (bituminous) coals and anthracites with an increase in the degree of metamorphic transformations of coal seams and a relatively low (atmospheric) gas pressure of 0.1 MPa. This advantage is lost at a pressure of 5 MPa. At high gas pressure (in the range of 1.0÷5.0 MPa), the dependence of sorption isotherms on the yield of volatile matter is most reliably described by a second-order polynomial. At a gas pressure of 0.1÷1.0 MPa, these dependencies are most realistically described by empirical equations of the sigmoid type.

Scientific novelty. For the first time, based on statistical processing of experimental data, it was established that with pressure changes within the range from 0.1 MPa to 5.0 MPa, a high correlation dependence of the sorption methane capacity of hard (bituminous) coals and anthracites on the yield of volatile matter at all stages of metamorphic transformations of coal seams was obtained. With an increase in pressure from 0.1 MPa to 5.0 MPa, an increase of four and more times in the standard deviations from the averaging curves is observed.

Practical value. The results of the research allow us to develop proposals for improving the regulatory framework in terms of forecasting the hazardous properties of coal seams during mining operations.

Keywords: coal, gas capacity, metamorphism, coal seams, safety.

1. Introduction

Gas capacity refers to the ability of geological formations, including fossil coals, to retain and accumulate gases under specific thermobaric conditions (i.e., defined temperature and pressure). It is assessed based on the volumetric content of gases – sorbed (both adsorbed and absorbed), dissolved, and free – converted to standard atmospheric conditions [1, 2]. This parameter is expressed per unit volume or mass of the rock. Gas capacity is a key characteristic in evaluating the gas-bearing potential of rock formations and is critically important in areas such as coal-seam methane recovery, underground gas storage, and mine safety assessments.

The gas content (methane content) of developed coal seams is one of the main parameters determining the gas content (methane content) of mine workings and the outburst hazard of seams. Its value is necessary for predicting the gas content of working and development faces, choosing a method for managing methane emission, predicting the outburst hazard of coal seams, conducting blasting operations on coal, etc. [3].

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Sorption involves the absorption of a substance from the environment by a solid or liquid. The relative gas content gradient is used to determine the general patterns governing the development of coal sorption capacity and the natural regional methane saturation of coal seams [4]. One of the promising areas of scientific research is the study of the sorption properties of coal and the prediction of natural gas content based on these properties [5, 6]. Long-term experimental studies have confirmed that the most influential factors determining the methane capacity of coal are pressure, temperature, and the degree of metamorphic transformation of coal seams. The methane capacity of coal, governed by its sorption ability, shows a direct correlation with the degree of metamorphism and pressure, and an inverse correlation with temperature [5, 7].

2. Methods

Analysis of sorption isotherms showed that a sharp and intensive increase in sorption occurs within a relatively narrow range of initial pressures (up to 2–3 MPa). Further increases in pressure lead to a progressively slower growth in sorption, which is attributed to the limited adsorption potential and the active volume of the coal. Near-complete gas saturation of coal is typically observed at pressures of 5–6 MPa, beyond which additional pressure has little effect on the sorption process.

Based on the conducted research [5–7], reference diagrams were constructed to illustrate the relationship between gas content and sorption methane capacity of coal at a pressure of 5 MPa, as a function of the degree of coal metamorphism.

These reference diagrams were constructed based on the assumption that the natural methane content of bituminous coals across all metamorphic stages – including low-metamorphosed anthracites of group $10A_1$ – is close to their sorption capacity at pressures up to 5 MPa. For coal samples collected from depths of up to 2600 meters, the natural gas content approaches the sorption capacity observed at pressures of 5–6 MPa, although it remains on average 10–20% lower. Significant discrepancies between natural gas content and sorption methane capacity were observed in anthracites starting from group $10A_1$, and particularly in super-anthracites of groups $10A_1$ – $10A_2$ and higher [5, 6].

In constructing the reference diagrams, gas content values were primarily derived from samples collected at depths ranging from 500–700 to 1000–1500 meters. According to the authors [5, 7], at these depths, the natural gas content stabilizes and approaches the methane sorption capacity of coal at a pressure of 5 MPa. As an example of a certain correlation between the averaged values of natural gas content and methane capacity – with respect to the burial depths of coal seams (l_1, l_2, l_3) and pressures up to 5 MPa – graphs illustrating their variation are presented (Fig. 1). Stabilization of average gas capacity values ($\overline{x}$) was observed at approximately 16.5 m^3/t of daf mass. The experimental values of individual gas content determinations were approximately equal in number to the established level of gas capacity, either higher or lower. The overestimated and underestimated gas content values corresponded to average values of 21 m^3/t of daf mass and 12 m^3/t of daf mass, respectively.

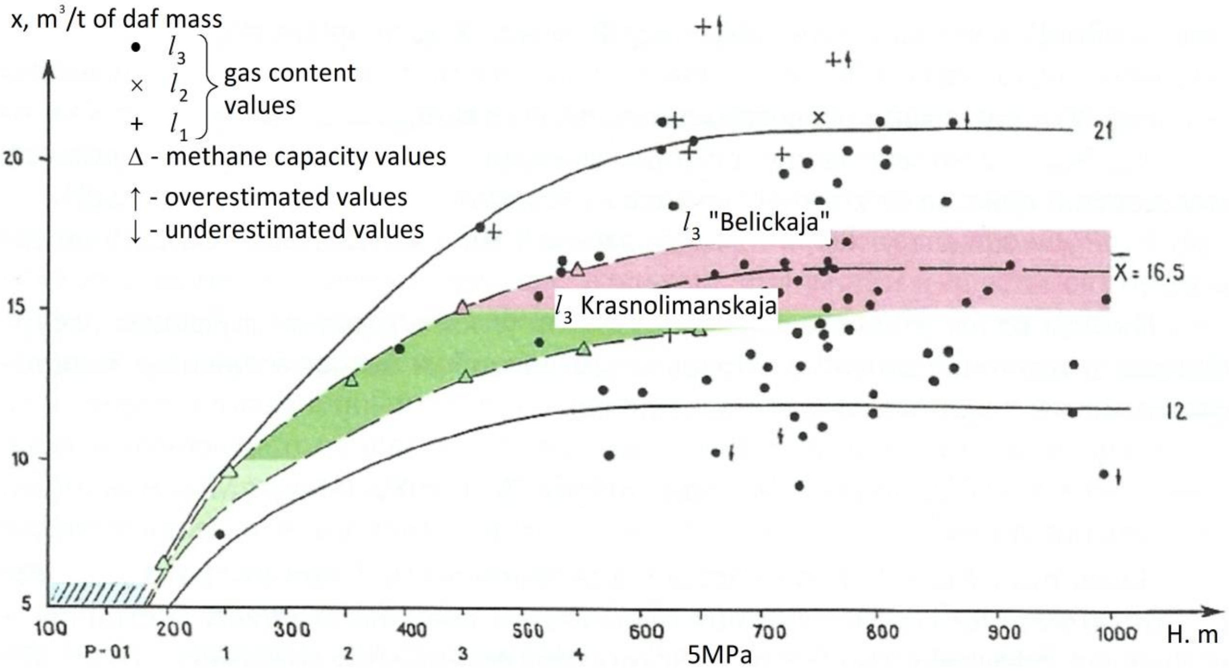


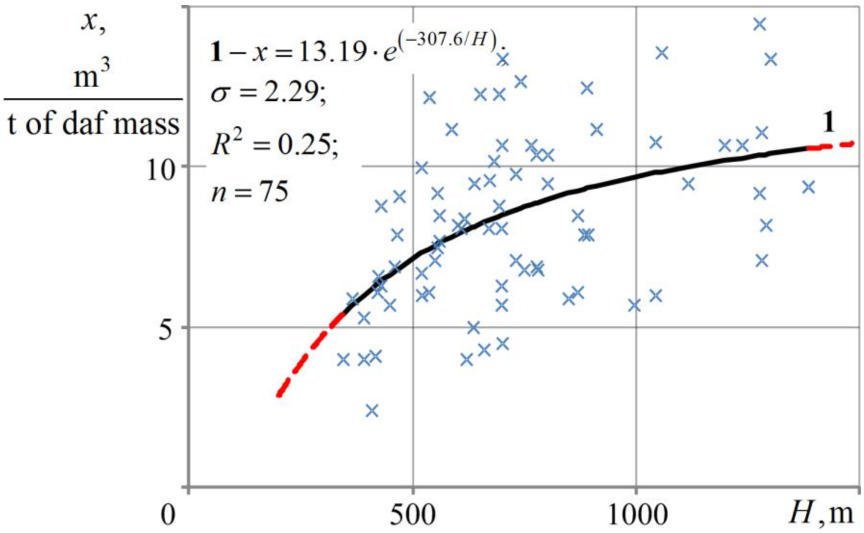
Figure 1 – Comprehensive assessment of coal gas content using the graphical-analytical method with control of the latter by methane capacity values (Graph of changes in gas content (x) of the coal seams l_1, l_2, l_3 of the Krasnolimanskaya mine with depth (H) [7])

Underestimated values of natural gas content, relative to gas capacity, were attributed to increased gas losses during the retrieval of core samples from greater depths, primarily due to the lack of airtightness in gas coring devices. In practice, a correction factor of 1.3 was sometimes applied to account for this deficiency. The causes of overestimated gas content values, however, have not been conclusively determined.

Methane capacity is measured under laboratory conditions. Due to the inability to fully replicate natural geological conditions in the laboratory, these values typically differ from the actual in-situ methane capacity of coals [8]. In such cases, the measured gas capacity of coal is influenced only by three factors: the coal's intrinsic sorption properties and the artificially controlled experimental conditions – namely temperature and pressure.

The primary factors that determine the methane content of coal-bearing formations include the degree of coal metamorphism, sorption capacity, porosity and gas permeability of the strata, moisture content, geological history of the basin, burial depth, hydrogeological conditions, and the coal saturation of the deposit [9]. Among these factors, only sorption capacity directly and simultaneously influences both the methane sorption capacity of coals and the actual methane content of mineable seams.

Many researchers, including [5–7], attributed the increase in methane content largely to the greater burial depth of mineable coal seams (see Fig. 1). A similar depth-dependent trend in gas content was identified for coal seam l_4 under the geological conditions of the D.F. Melnikov Mine, PJSC "Lysychanskvugol" (see Fig. 2).



× – experimental values for determining gas content; 1 – averaging curve;
σ – standard deviation; R^2 – determination coefficient; n – number of processed data pairs

Figure 2 – Graph of changes in gas content (x) of the coal seam l_4 of the D.F. Melnikov mine with depth (H) [10]

The results of statistical analysis of the experimental data [10] revealed a weak correlation between the gas content of the coal seams and their burial depth. The coefficient of determination (R^2) and the standard deviation (σ) were found to be 0.25 and 2.29 m^3/t of daf mass, respectively. These findings indicate that, in addition to burial depth, other factors also significantly influence the gas content of coal seams.

In the present case, the degree of metamorphic transformation of coal seams does not appear to be a primary factor influencing gas content. This is evidenced by the practical constancy of the metamorphism indicator across all seams within the boundaries of the mine fields (Table 1). According to the definition provided in [11], metamorphic rocks are those that have undergone changes in mineral composition under the influence of fluids, temperature, and pressure.

The main indicator of the metamorphic transformation of fossil coals is the elemental carbon content in the organic matter. The carbon content functionally controls the total concentration of other main components in the organic matter – namely hydrogen, oxygen, nitrogen, and organic sulfur. The elemental composition of coal on a combustible mass (Table 1) shows only minor differences compared to its composition on an organic mass. This is due to preliminary coal beneficiation, with ash content reduced to below 10% during preparation of analytical samples for laboratory testing [12].

The elemental carbon content on a combustible mass (C_c) within the boundaries of the Krasnolimanskaya and D.F. Melnikov mine fields varied only slightly. For these mines, the C_c values ranged from 83.1% to 84.0% and from 77.3% to 79.2%, respectively [14, 15] (see Table 1). With a difference in the depth of the seams within the boundaries of the mine fields of several hundred meters, the difference in the elemental carbon content was less than two percent.

Table 1 – Information on metamorphic transformation indicators of coal seams at the Krasnolimanskaya and D.F. Melnikov mines

Mine	Coal seam	Sources of information									
		Catalog [13]			Reference Book (Handbook) [14]						
		M	*H*, m	*x*, m³/t	*M*	V^{daf}	$C_г$	$H_г$	$S_г$	$N_г$	$O_г$
Krasno-limanskaya	l_7	Г	564	5.0	Г	35.3	83.3	5.2	2.2	1.5	7.8
	l_3	Г	505	4.0	Г	35.6	–	–	–	–	–
D.F.Melnikov mine	l_6	Г	468	5.0	Д	40.0	79.2	4.7	1.2	1.5	12.9
	l_5				Д	42.5	–	–	–	–	–
	l_4	Г	668	5.0	Д	44.0	–	–	–	–	–
	l_3				Д	43.5	77.3	5.5	5.0	1.4	10.8
	l_2^1	Г	618	4.0	Г	44.0	79.2	5.5	4.4	1.3	9.6
	k_8	Г	618	4.0	Д	44.0	78.8	5.2	4.5	1.7	9.8
	k_7^1	–	–	–	–	–	–	–	–	–	–
	k_7	–	–	–	–	–	–	–	–	–	–

Mine	Coal seam	Sources of information									
		Catalog [16]				Reference Book (Handbook) [15]					
		M	H_1, m	H_2, m	x_1 / x_2	*M*	V^{daf}	$C_г$	$H_г$	$S_г$	$O_г$+$N_г$
Krasno-limanskaya	l_7	Г	518÷568	875÷925	15.0 / >15.0	Г	35.6	84.0	5.3	2.2	8.5
	l_3	Г	716÷766	875÷975	20.0 / >15.0	Г	36.0	83.1	5.4	2.9	8.6
	$k_8^н$	ГЖ	–	900	15.0 / >15.0	–	–	–	–	–	–
	k_7	Ж	–	900	20.0 / >20.0	–	–	–	–	–	–
	k_5	ГЖ	708	850	20.0 / 25.0	–	–	–	–	–	–
D.F.Melnikov mine	l_6	Д, Г	750	1150	10.0 / 10.0	Д	40.6	78.8	5.3	2.1	13.8
	l_5	Д, Г	750	1150	10.0 / 10.0	Г	43.4	–	–	–	–
	l_4	Г	825	1150	12.0 / 12.0	Г	41.2	79.7	5.4	2.0	13.9
	l_3	Г	–	1150	– / 12.5	–	–	–	–	–	–
	l_2^1	Г	750	1150	12,0 / 12.5	Г	43.4	79,2	5.4	2.2	13.2
	k_8	Г	750	1150	15,0 / 15.0	Г	43.4	78.1	5.6	3.8	12.5
	k_7^1	Г	550	1150	10 / 15.0	–	–	–	–	–	–
	k_7	Г	–	1150	– / 15.0	–	–	–	–	–	–

Note to Table 1: *H* – maximum depth of mining operations, m; H_1, H_2 – depth of the lower contour of mining operations and lower boundary of the mine field, respectively, m; *M* – coal grade; *x* – gas content of the coal seam, m³/t; x_1, x_2 – maximum natural gas content of the coal seam at the lower contour of mining operations and at the lower boundary of the mine field, respectively, m³/t of daf mass; V^{daf} – yield of volatile matter on a dry ash-free mass, %; *C*c, *H*c, *S*c, *N*c, *O*c – elemental composition on a combustible basis, respectively, of carbon, hydrogen, sulfur, nitrogen and oxygen, %.

Additional criteria in assessing the metamorphic transformations of coal seams are the grade of coal and the yield of volatile matter during thermal decomposition of coal without air access (V^{daf}). In the conditions of the Krasnolimanskaya mine, with a change in the depth of seams in the range of 505÷975 m, coals were classified as grade "Г" (Gas coal, bituminous) [13–15]. According to the catalog [16], coals of the underlying seams $k_8^{н}$, k_7 and k_5 are classified as grades "ГЖ" (Gas-fat coal or weak coking coal) and "Ж" (Coking coal, fat coal) see Table 1. In the conditions of the D.F. Melnikov mine, in the interval of seam occurrence of 468÷1150 m, coals are classified only as grades "Д" (Long-flame coal or flame coal sub-bituminous/bituminous) and "Г" (Gas coal, bituminous) [13–16]. Coal grades only conditionally designate their varieties, similar in genetic features and main energy and technological characteristics [17].

Some of the reliable results of experimental determination of coal seam quality indicators from various coal basins, obtained in previous years using analytical chemistry methods, are presented in reference and regulatory documents [13–16]. These data, along with certain other findings, remain relevant today for addressing a range of current geological problems related to understanding the processes of coal formation [18] and the manifestation of hazardous properties of coal seams during mining operations [19]. The justification and development of methods for utilizing the results of coal quality assessments enable the efficient use of existing scientific findings and experimental data on the composition and properties of coals from various basins to solve other pressing issues [18, 19].

The most studied criteria for assessing the degree of metamorphic transformations of coals include the V^{daf} indicator. This parameter is used both to assess the consumer qualities of coals and to predict the hazardous properties of coal seams during mining operations. At the Krasnolimanskaya Mine, V^{daf} values ranged from 35.3% to 36.0%, while at the D.F. Melnikov Mine, V^{daf} for all seams was within 40÷44% (Table 1).

The presented experimental data indicate a virtually identical degree of metamorphic transformations of coals within the boundaries of mine fields, regardless of the depth of occurrence of the seams. The V^{daf} indicator does not directly characterize changes in the elemental composition, but its values are stable within the boundaries of each mine field. This is confirmed by statistical models of the V^{daf} indicator for more than two thousand coal seams [20].

Under the geological conditions of the two mines under consideration, where the coal seams exhibit a uniform degree of metamorphic transformation, only a general trend of increasing gas content with depth is observed (Fig. 1 and 2). This indicates the absence of a strong correlation between gas content and depth of seam occurrence, and consequently, between gas content and the degree of coal metamorphism in the studied conditions.

According to B.M. Kosenko, the gas content of coals and anthracites in Donbass reaches its maximum at depths from 600 m to 1300 m, and then begins to decrease. According to the data presented in the report of the US Environmental Protection

Agency (EPA) from December 2011, the gas content of coal seams in the Karaganda basin of Kazakhstan reaches a maximum at depths of 400 m to 500 m, where the gas content is 15–20 m³/t. Then the gas content stabilizes at a level of 22–27 m³/t at depths of 600 m to 1300 m. The depth of the gas weathering zone varies from 60 m to 250 m. These data confirm the information provided by M.A. Ermekov that in the Karaganda basin the maximum gas content of hard coals and anthracites is observed at depths of about 500 m. In the Bokovo-Khrustalny district of the Donbas region, the maximum natural gas content in anthracite seams was recorded at a depth of approximately 300 meters [21]. This phenomenon is presumably associated with a reduction in the sorption capacity of coal due to increasing temperature with depth, as well as with the diminishing ability of anthracite to generate methane as the degree of metamorphism increases.

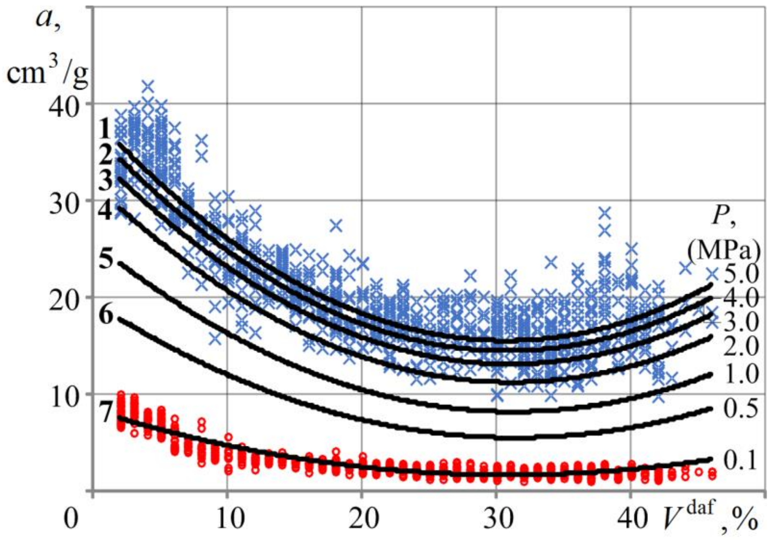
In this case, the methane capacity of anthracite is presumed to differ from the sorption properties of hard coal, due to differences in the degree of metamorphic transformation of the seams. The opposite trends in gas content variation with depth observed in hard coals and anthracites suggest a possible increase in the discrepancy between sorption-based methane capacity and actual gas content in anthracite seams. This significant mismatch may not be attributed solely to the degree of metamorphism, but also to the direct relationship of sorption capacity with pressure and its inverse dependence on temperature – both of which unequivocally increase with depth. This highlights a degree of uncertainty in estimating the gas content of coal at all stages of metamorphic transformation. Consequently, the averaged reference methane capacity diagrams proposed in [5–7] cannot be reliably applied to predict gas content in anthracite seams at advanced stages of metamorphism. However, the strong correlation between sorption-based methane capacity and metamorphic indicators across all transformation stages provides a basis to assume that gas content in anthracite seams, at a minimum, is influenced by additional geological factors beyond metamorphism alone.

Objective – to determine the indicators of the strength of the correlation between the sorption methane capacity of coals and anthracites and the degree of metamorphic transformation of coal seams with changes in pressure and temperature conditions.

The research methodology involves statistical processing by the least squares method of experimentally established values of methane capacity (a) of fossil coals, including anthracites [22], from the indicator of the yield of volatile matter during thermal decomposition of coals without air access (V^{daf}). Pressure (P) during laboratory experiments and temperature (t), corresponding to the depth of occurrence of the coal seams, were considered as additional influencing factors.

3. Results and discussions

The results of statistical processing of the dependence of the sorption methane capacity of coals and anthracites of the Donetsk and Lviv-Volyn basins on the yield of volatile matter (V^{daf}) and pressure (P) are shown in the graph (Fig. 3) and summarized in Table 2. When changing the pressure within the range from 0.1 MPa to 5.0 MPa, in all cases a high correlation dependence of the sorption methane capacity of hard coals and anthracites (a) on the yield of volatile matter (V^{daf}) was obtained. This is evidenced by the high values of the determination coefficients (R^2=0.81÷0.87). With an increase in pressure from 0.1 MPa to 5.0 MPa, a significant increase (four times) in the standard deviations (σ) is observed, respectively, from the averaging curves 1 and 7 (σ_1 = 0.74 cm^3/g and σ_7 = 3.00 cm^3/g, Fig. 3, Table 2).



×, ○ – experimental data [22], respectively, at P=5.0 MPa and P=0.1 MPa;
1–7 – empirical averaging curves of a second-order polynomial, obtained by the least squares method, respectively, at pressure P from 0.1 MPa to 5.0 MPa

Figure 3 – Dependence of the sorption methane capacity (a) of fossil coals on the yield of volatile matter (V^{daf}) at different pressure values (P)

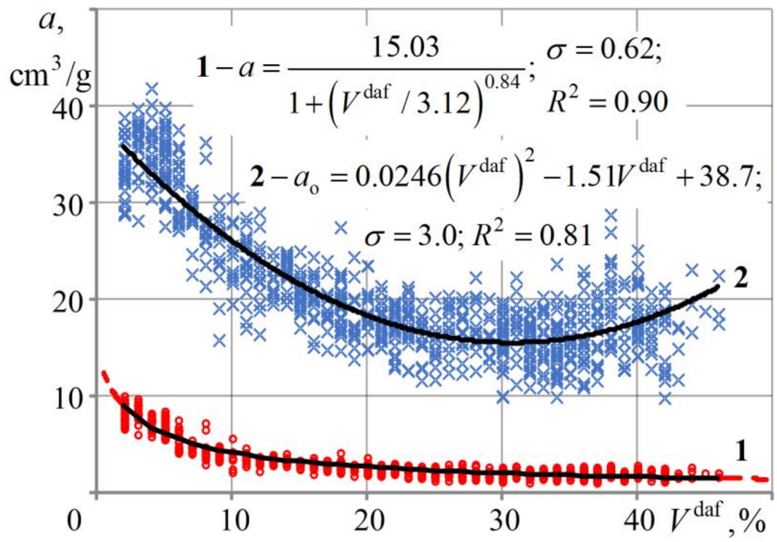
Table 2 – Results of statistical processing of experimental data [22] on establishing isothermal dependencies (t=30°C) of methane capacity of coals (a) on the yield of volatile matter (V^{daf}) at fixed pressure values (P)

Curves	Pressure P, MPa	Empirical dependencies of methane sorption capacity (second-order polynomials)	Equation number	Indicators of correlation strength		
				n, pcs.	R^2	σ, cm^3/g
1	0.1	$a = 0.0070\left(V^{daf}\right)^2 - 0.434V^{daf} + 8.29$	(1)	776	0.86	0.74
2	0.5	$a = 0.0142\left(V^{daf}\right)^2 - 0.893V^{daf} + 19.47$	(2)	776	0.87	1.51
3	1.0	$a = 0.0179\left(V^{daf}\right)^2 - 1.122V^{daf} + 25.68$	(3)	776	0.86	1.94
4	2.0	$a = 0.0212\left(V^{daf}\right)^2 - 1.320V^{daf} + 31.75$	(4)	776	0.85	2.36
5	3.0	$a = 0.0228\left(V^{daf}\right)^2 - 1.410V^{daf} + 34.95$	(5)	776	0.84	2.63
6	4.0	$a = 0.0239\left(V^{daf}\right)^2 - 1.474V^{daf} + 37.14$	(6)	776	0.82	2.87
7	5.0	$a_o = 0.0246\left(V^{daf}\right)^2 - 1.510V^{daf} + 38.70$	(7)	776	0.81	3.00

Note to Table 2: n is the number of processed data pairs; R^2 is the coefficients of determination; σ is the standard deviation.

High pressure (5 MPa and more) causes not only an increase in the standard deviations from the averaging curves, but also leads to a change in the type (character) of the dependence of the sorption methane capacity on the yield of volatile matter. This is evident in the example of low-metamorphosed hard coals (V^{daf} > 30%, Fig. 3) by the location of individual values of the sorption methane capacity for each coal seam at a pressure of 5.0 MPa and 0.1 MPa. At high pressure (5 MPa), with an increase in the influence of metamorphic processes (a decrease in the V^{daf} values to 30%), the sorption capacity of hard coals decreases. A further increase in the influence of metamorphic processes (V^{daf} < 30%) contributes to an increase in the sorption capacity of both hard coals and anthracites. Its maximum values (up to 40 cm^3/g and more) are achieved for anthracite seams (V^{daf} < 10%).

At atmospheric pressure (P=0.1 MPa), with an increase in the degree of metamorphic processes (further decrease in the V^{daf} values), only a one-sided increase in the sorption methane capacity of fossil coals is observed (Fig. 3). This one-sided nature of the change in experimental data does not correspond to the shape of the curves of the second-order polynomial at a pressure of 0.1 MPa. The effect of pressure (P) on the one-sided nature of the relationship between the sorption capacity (a) and the yield of volatile matter (V^{daf}) is confirmed by experimental data at a pressure of 0.1 MPa (Fig. 4).



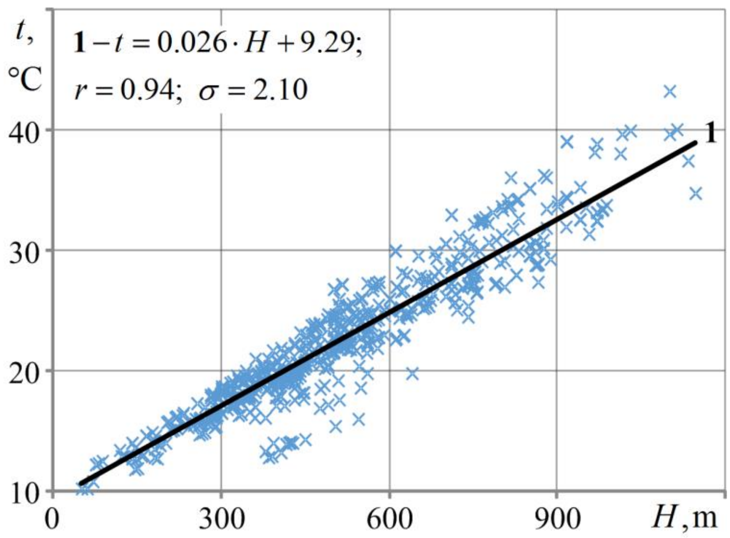
×, ○ – experimental data [22] at P=0.1 MPa and P=5.0 MPa, respectively;

1 – empirical dependence of sigmoid, obtained by the least squares method, at pressure P=0.1 MPa and temperature t=30°C;
2 – empirical dependence of the second-order polynomial, established by the least squares method, at pressure P=5.0 MPa and temperature t=30°C;
σ – standard deviations; R^2 – determination coefficients

Figure 4 – Dependence of the sorption methane capacity of coals and anthracites (a) on the yield of volatile matter (V^{daf}) at a pressure (P) of 0.1 and 5 MPa

The values of the indicators of correlation strength of the sigmoid curve 1 (R^2=0.90, σ=0.62 cm^3/g) are somewhat higher compared to the empirical dependence of the second-order polynomial at a pressure of 0.1 MPa (Table 2, curve 1, R^2=0.86, σ=0.74 cm^3/g). The sigmoid more reliably reflects the one-sided nature of the change in the sorption methane capacity of hard coals and anthracites with an increase in the degree of metamorphic transformations of the mine seams and a relatively low (atmospheric) gas pressure of 0.1 MPa. This advantage is lost at a pressure of 5 MPa. The indicators of the closeness of the correlation connection for this case (R^2=0.77, σ=3.35 cm^3/g) are somewhat worse compared to the indicators of the second-order polynomial (Fig. 4, curve 2, R^2=0.81, σ=3.0 cm^3/g). This additionally indicates a change in the nature of the dependence of the sorption capacity of low metamorphic grade coals to the opposite with an increase in gas pressure.

The temperature of the rocks containing coal seams is directly proportional to the depth of their occurrence. The temperature regime for each of the coal seams considered [22] was determined experimentally or calculated taking into account the geothermal stage and the average temperature on the earth's surface (Fig. 5).



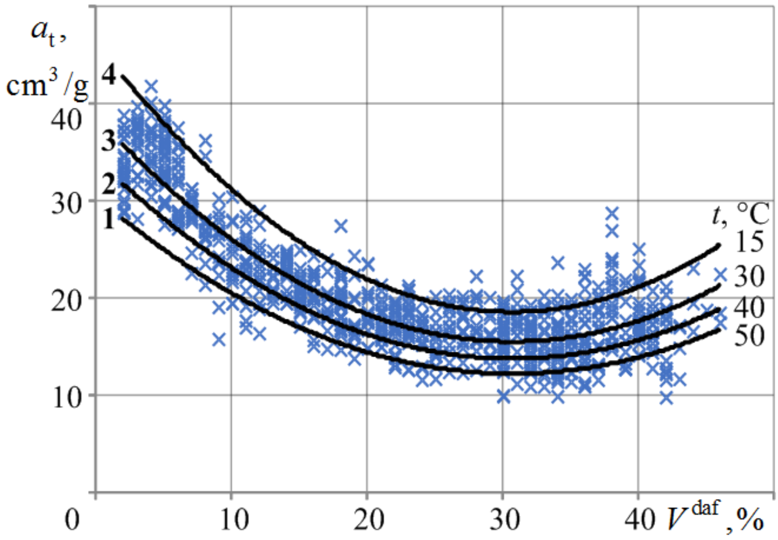
× – experimental data or calculated values using geothermal stage data;
1 – averaging line; σ – standard deviation; r – correlation coefficient

Figure 5 – Dependence of rock temperature (t) on the depth of occurrence of coal seams (H) according to the catalog [22]

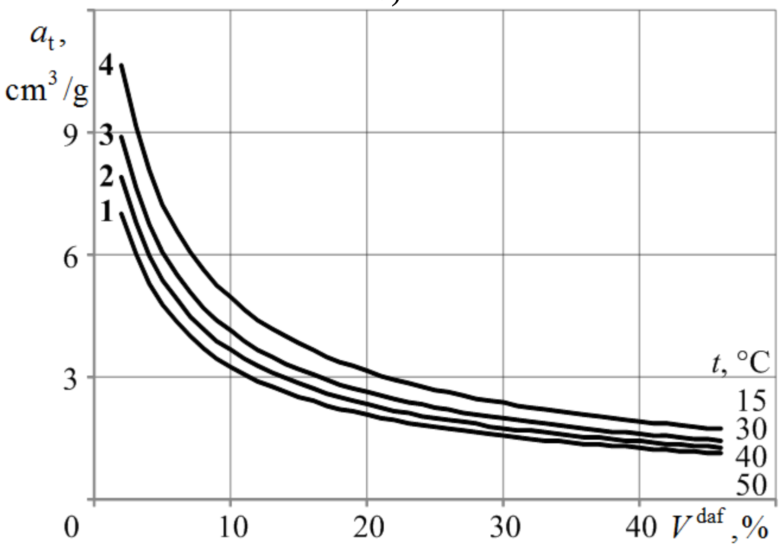
The temperature change range for the studied coal seams varied from approximately 10°C to 50°C. To analyze the influence of the temperature factor, sorption isotherms were considered at temperatures of 15°C, 30°C, 40°C, and 50°C, respectively. The sorption isotherm (a_o) was determined experimentally for a temperature of 30°C and a pressure of 5.0 MPa. The sorption methane capacity (a_t) at any temperature (t) other than 30°C was established by introducing the correction [22]:

$$a_t = 1.433 \cdot a_o \cdot \exp(-0.012 \cdot t), \text{ cm}^3/\text{g}. \quad (1)$$

Taking into account the different nature of the change in the dependence of the sorption methane capacity at high (5.0 MPa) and low (0.1 MPa) pressures, the selection of sorption isotherm curves was made separately for these extreme pressure values (Fig. 6, Table 3).



a)



b)

× – initial experimental data [22] (at P=5.0 MPa, t=30°C);

1, 2, 3, 4 – sorption isotherm curves, respectively, at temperatures of 50°C, 40°C, 30°C and 15°C

Figure 6 – Isotherms of methane sorption capacity of coals and anthracites (a_t) at pressure (P) of 5.0 MPa (a) and 0.1 MPa (b) depending on the yield of volatile matter (V^{daf})

At high gas pressure (in the range of 1.0÷5.0 MPa), the dependence of sorption isotherms on the yield of volatile matter is most reliably described by a second-order polynomial (Fig. 6, a, Table 3). At gas pressure of 0.1÷1.0 MPa, these dependencies are most realistically described by empirical equations of the sigmoid type (Fig. 6, b, Table 3).

Table 3 – Results of statistical processing of experimental data [22] on establishing isothermal dependencies of the sorption methane capacity of coals and anthracites (a_t) at a pressure of 5.0 MPa and 0.1 MPa

Curves	Pressure P, MPa	Empirical dependencies of methane sorption capacity (second-order polynomials)	Equation number	Indicators of correlation strength		
				n, pcs.	R^2	σ, cm³/g
at a pressure of 5.0 MPa						
1	50	$a_t = 0.0194\left(V^{daf}\right)^2 - 1.189V^{daf} + 30.44$	(1)	776	0.81	2.38
2	40	$a_t = 0.0218\left(V^{daf}\right)^2 - 1.341V^{daf} + 34.32$	(2)	776	0.81	2.68
3	30	$a_o = 0.0246\left(V^{daf}\right)^2 - 1.512^{daf} + 38.69$	(3)	776	0.81	3.00
4	15	$a_t = 0.0295\left(V^{daf}\right)^2 - 1.810V^{daf} + 46.32$	(4)	776	0.81	3.62
at a pressure of 0.1 MPa						
1	50	$a_t = \dfrac{11.823}{1+\left(V^{daf}/3.12\right)^{0.84}}$	(5)	776	0.90	0.49
2	40	$a_t = \dfrac{13.330}{1+\left(V^{daf}/3.12\right)^{0.84}}$	(6)	776	0.90	0.55
3	30	$a_t = \dfrac{15.030}{1+\left(V^{daf}/3.12\right)^{0.84}}$	(7)	776	0.90	0.62
4	15	$a_t = \dfrac{17.994}{1+\left(V^{daf}/3.12\right)^{0.84}}$	(8)	776	0.90	0.74

Note to Table 3: n is the number of processed data pairs; R^2 is the coefficients of determination; σ is the standard deviation.

4. Conclusions

The conducted research has led to important conclusions regarding the nature of metamorphic transformations in coal seams and the development of their hazardous properties related to gas content. The obtained results are relevant and they are necessary for improving the regulatory framework for safe mining operations. The summarized conclusions are as follows:

– when compiling reference diagrams of gas content growth, it was primarily associated with the depth of coal seam occurrence. Based on experimental data, only a certain tendency of such a relationship is established;

– within the boundaries of mine fields, regardless of the depth of seam occurrence, the degree of metamorphic transformation of coal remains nearly uniform;

– in different coal basins, the maximum gas content of coal seams is reached at varying depths of occurrence. In some cases, this is associated with differing degrees of coal metamorphic transformation;

– the opposite trends in gas content variation of hard (bituminous) coal and anthracite with increasing depth lead to a growing discrepancy between the sorption methane capacity and the actual gas content of anthracite seams;

– to date, there remains some uncertainty in the assessment of the gas content of fossil coals at all stages of metamorphic transformation of coal seams;

– when the pressure varies from 0.1 MPa to 5.0 MPa, a strong correlation is observed between the sorption methane capacity of hard (bituminous) coal and anthracites and their volatile matter yield across all stages of metamorphic transformation of coal seams;

– with increasing pressure from 0.1 MPa to 5.0 MPa, the root-mean-square deviations from the average curves increase by a factor of four and more;

– high pressure (1 MPa and more) leads to a change in the nature of the dependence between sorption methane capacity and volatile matter yield in low-metamorphosed hard (bituminous) coals;

– the maximum sorption capacity of up to 40 cm³/g and more is achieved at a volatile matter yield below 10% and a pressure of 5.0 MPa;

– at atmospheric pressure (0.1 MPa), a unidirectional increase in sorption methane capacity is observed with an increasing influence of metamorphic processes. The high coefficient of determination of this empirical relationship (R^2=0.90) enables its use for estimating the residual gas content of coal when forecasting the gas emission potential of mine workings;

– the influence of increasing coal seam depth on the sorption capacity of coal is associated with the rising temperature of the surrounding rock. Matching laboratory gas pressure conditions to in-situ mining pressure requires further investigation.

Conflict of interest

Authors state no conflict of interest.

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About the author

Rudniev Yevhen, Doctor of Technical Sciences (D.Sc.), Associate Professor, Professor of the Department of Electrical Engineering, Professor of the Department of Pharmacy, Production and Technology, Volodymyr Dahl East Ukrainian National University (VDEUNU), Ukraine, Kyiv, rudnev_es@snu.edu.ua ***(Corresponding author)***, ORCID ***0000-0002-4236-8407***

ПРО ЗАЛЕЖНІСТЬ ГАЗОЄМНІСТІ ВИКОПНОГО ВУГІЛЛЯ ВІД СТУПЕННЯ МЕТАМОРФІЧНИХ ПЕРЕТВОРЕНЬ ШАХТОПЛАСТІВ

Руднєв Є.

Анотація. Мета: встановити показники тісноти кореляційної залежності сорбційної метаноємності кам'яного вугілля та антрацитів від ступеня метаморфічних перетворень шахтопластів при зміні тиску та температури.

Методика досліджень передбачає статистичну обробку методом найменших квадратів експериментально встановлених значень метаноємності (*a*) кам'яного вугілля та антрацитів, від показника виходу летких речовин при термічному розкладанні вугілля без доступу повітря (V^{daf}). В якості додаткових впливаючих факторів розглянуті значення тиску (*P*) при проведенні лабораторних експериментів і температури (*t*), що відповідає глибині залягання вугільних пластів.

Результати. При зміні тиску в межах від 0,1 МПа до 5,0 МПа у всіх випадках отримана висока кореляційна залежність сорбційної метаноємності кам'яного вугілля та антрацитів (*a*) від виходу летких речовин. Високий тиск

(5 МПа і більше) викликає не тільки збільшення середньоквадратичних відхилень від усереднених кривих, але й призводить до зміни виду (характеру) залежності сорбційної метаноємності від виходу летких речовин. При атмосферному тиску (*P*=0,1 МПа), з посиленням ступеня метаморфічних процесів (подальшому зменшенні значень V^{daf}), спостерігається лише одностороннє зростання сорбційної метаноємності викопного вугілля. Сигмойда більш достовірно відображає односторонній характер зміни сорбційної метаноємності кам'яного вугілля та антрацитів при посиленні ступеня метаморфічних перетворень шахтопластів та відносно низькому (атмосферному) тиску газу 0,1 МПа. Така її перевага втрачається при тиску 5 МПа. При високому газовому тиску (в діапазоні 1,0÷5,0 МПа) залежність ізотерм сорбції від виходу летких речовин найдостовірніше описується поліномом ступеня другого порядку. При газовому тиску 0,1÷1,0 МПа найбільш реально ці залежності описуються емпіричними рівняннями типу сигмойди.

Наукова новизна. Вперше на підставі статистичної обробки експериментальних встановлено, що при зміні тиску в межах від 0,1 МПа до 5,0 МПа отримано високу кореляційну залежність сорбційної метаноємності кам'яного вугілля та антрацитів від виходу летючих речовин на всіх стадіях метаморфічних перетворень шахтопластів. Зі зростанням тиску від 0,1 МПа до 5,0 МПа спостерігається збільшення в чотири і більше разів середньоквадратичних відхилень від усереднених емпіричних кривих.

Практичне значення. Результати досліджень дозволяють розробити пропозиції щодо вдосконалення нормативної бази в частині прогнозу небезпечних властивостей шахтопластів при веденні гірничих робіт.

Ключеві слова: вугілля, газоємність, метаморфізм, шахтопласти, безпека.