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THE DOUBLE EXPONENTIAL MODEL FOR PREDICTING NATURAL REGIONAL GAS CONTENT OF COAL BEDS

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Abstract. Methane is a powerful greenhouse gas. Methane is the main component of coalfield gases, and since almost the entire coal-bearing strata of rocks is saturated with methane, coal production in coal mines during their exploitation and after the completion of cleaning operations is constantly accompanied by the methane release into the mined space. According to predictions, its emissions from operating underground workings will have increased quantitatively by 4 times by the year 2100, and emissions from closed mines by 8 times. Therefore, predicting its emissions into the atmosphere based on estimating the gas content of coal beds is an urgent modern objective and will remain relevant in the future.

The purpose of the work was to develop a new method for predicting the methane content of coal beds for coal of different grades according to the occurrence depth.

For the previously set dependence of the relative gradient of methane content in coal beds on the occurrence depth, the authors propose a biexponential model, which is universal for determining the gradient of methane content in coal beds of different stages of metamorphism. The new biexponential model has a physical foundation – it is based on the dependence of methane content on the sorption capacity of coal, which, in turn, is determined by pressure (depth). With this model, the natural methane content increases rapidly with increasing pressure up to 6 MPa. Then it increases slowly and slightly up to 10 MPa, reaching its maximum (maximal potential gas-bearing capacity for the corresponding degree of coalification at depths of approximately 1200 m), with subsequent stabilization. The obtained dependences of the relative gradient of gas content on depth and gas pressure for different grades of metamorphism were used to develop a method for predicting the natural regional background gas content of coal beds by determining the limiting sorption capacity of coal. The method allows for determining the natural methane content of coal of different degrees of metamorphism, considering the occurrence depth, with correction for moisture and ash content.

Keywords: Donbas, coal beds, natural gas content, sorption capacity.

1. Introduction

Methane is a powerful greenhouse gas, the global warming potential (GWP) of which, according to [1], is 28–36 times higher than the corresponding potential of carbon dioxide over a century. However, after 10 years, its GWP is 84 times higher due to the 12 years of its existence in the atmosphere. Coal mines are one of the largest sources of anthropogenic methane emissions. Methane is the main component of coalfield gases, and since almost the entire coal-bearing strata of rocks is saturated with methane, coal production in coal mines during their operation and after the completion of cleaning operations is constantly accompanied by the methane release into the mined space. Based on data on world coal production, the authors of the work [1] concluded that by 2100, methane emissions from operating underground mines will have increased quantitatively by 4 times, and emissions from closed mines by 8 times. In this regard, the problem of methane from coal and gas fields will not lose its relevance in the future.

The sources of methane inflow in mines include the coal bed being developed (both destroyed coal and its exposed surfaces on the walls of the mine workings), the underworked and overworked coal-rock massif (beds-satellites and host rocks in the roof and bottom of the commercial bed), and the produced space of spent longwalls. A significant portion of methane emissions from mines is released into the atmosphere in an uncontrolled and unguided manner. Methane emissions from mines are an inevitable by-product of the coal mining cycle and can continue for decades after the

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completion of mining operations and the closure of coal mines, even with active actions to mitigate this harmful impact.

Ukraine owns significant gas resources from coal fields. At the same time, during the extraction of 1 ton of coal, on average, 20 cubic meters of methane are released. Most of it is emitted into the atmosphere, and only a small amount is utilized. Preventing the harmful impact of coalmine methane on the environment by reducing emissions into the atmosphere is the goal of special projects for the extraction and utilization of emission gas. Predicting methane emissions from operating and closed mines is an urgent task and involves determining the natural gas content of coal beds. The gas content of coal beds being developed is one of the main parameters determining the methane volume of mining workings, the outburst hazard of coal beds, and the emission volume of methane into the atmosphere. The research of the gas content of coal beds and the gas sorption properties of coal is being conducted in all, without exception, coal mining basins in the world. In particular, in Canada and the USA [2], Australia [2, 3], China [4, 5], India [6], South Africa [7], Indonesia [8], Poland [9,10], and some other countries.

Predicting gas content requires a comprehensive approach that includes various methods and models. Each of the existing methods has its advantages and disadvantages, and the best results are achieved when they are used in combination. Predicting the gas content of coal beds demands objective data on the natural and residual gas content of coal beds, as well as an assessment of the effectiveness of degassing measures. [11, 12]. According to world experience, such information is typically obtained using various experimental techniques that involve direct measurement of gas release from coal samples or coal cores. Determining the gas content of coal beds in operating mines in most cases of world practice is based on the norms and requirements of the American standard ASTM D 7569-10 [13], the Australian standard AS 3980-1999 [14], the methodology of the Gas Research Institute [15] and the company DMT GmbH & Co [16].

The essence of the method for determining gas content in coal beds, as outlined in the ASTM D7569-10 standard [13], is the use of the direct desorption method to measure the gas content in coal. This method is widely used to estimate the amount of methane and other gases that may be released from coal during its production.

The method for predicting the gas content of coal beds, as outlined in Australian Standard AS 3980-1999 [14], is based on the direct desorption method, which determines the amount of gas contained in coal beds. The main objective of this method is to obtain an accurate estimate of the total gas content of coal, which is important for ensuring the safety of coal mining.

The Gas Research Institute methodology, described in the report GRI-94/0396 ("A Guide to Determining Coalbed Gas") [15], is based on a comprehensive approach to determining the gas content of coal beds. It was developed to estimate the amount of gas (mainly methane) that can be released from coal beds and is intended to provide data for forecasting and managing the gas potential of coal fields.

The method for determining the gas content of coal beds, developed by DMT GmbH & Co [16], is aimed at improving the efficiency of degassing and gas content management in low-permeability coal beds during longwall mining. The essence of the method is to combine relaxation methods and degassing wells to ensure high productivity and safety during mining in low-permeability coal beds.

All of the listed standards provide for the direct determination of gas content by measuring the amount of gas released from coal samples or borewells into hermetic measuring vessels. Each of these methods has shortcomings that may affect the accuracy and reliability of the results when determining the gas content of coal beds in operating mines.

The ASTM D 7569-10 standard [13] is intended for US conditions, which may differ from the geological conditions of other regions. It uses empirical relationships that do not always take into account local features of the beds and do not always take into account the impact of deep faults through which additional volumes of gas may flow.

The AS 3980-1999 standard [14] is focused on the peculiarities of coal mining in Australia. Therefore, it has specific geological conditions and makes certain assumptions about gas saturation that may not correspond to real conditions in other regions. It may also not take into consideration all degassing mechanisms in operating mines.

The Gas Research Institute [15] methodology may have limitations in terms of the accuracy of determining gas content at different stages of mine operation. However, it requires careful calibration for specific mine conditions and does not always allow for an accurate estimation of the impact of fracturing and deep faults.

The DMT GmbH & Co [16] methodology is focused on European standards, which may not meet the conditions of other countries. It may give errors in conditions of high gas saturation or active gas movement along tectonic faults. It does not always take into account changes in pressure and temperature that affect gas release from the beds.

In general, all methods require adaptation to specific mine conditions. Their application involves a large amount of field or mine work. In some cases, inaccuracy and significant scatter of measurement results by different methods may occur.

The purpose of the research is to develop a new method for predicting the methane content of coal beds for coal of different grades according to the occurrence depth.

The object of research is beds of all grades of coal – from long-flame to anthracite within the Donets coal basin.

2. Methods

To determine the sorption capacity of coal, a well-known volumetric method developed at the MakNDI [17] was used, which is based on the research of the methane-bearing capacity of coal beds at a pressure of up to 5 MPa and a temperature of +30 °C. Measurements were carried out under isothermal conditions with control of the stability of the temperature regime. To increase the accuracy of the experiment, each sample was subjected to multiple tests, and the obtained values were averaged.

The analysis of the natural gas content of coal beds was based on the results of geological exploration work, as well as direct and indirect methods for determining gas saturation. Sampling was carried out using specialized gas core samplers and formation testers (GKN, GK, KII-65), taking into account possible gas losses during transportation. Additionally, gas chromatography methods were used to determine the composition of the gas mixture, which allowed for the identification of the concentrations of methane, ethane, carbon dioxide, and other components.

Experimental data processing was conducted using mathematical statistics methods, particularly correlation and regression analysis, variance analysis to assess deviations in methane-bearing capacity values.

3. Results and discussion

The natural methane content of coal beds is determined by the sorption capacity of coal since methane is found in coal mainly in adsorbed and absorbed form. The proportion of free gas in coal beds is insignificant; the free gas content is from 5–7%, and the maximum is 10–13%. The potential gas recovery of coal beds is usually due to the extraction of mainly sorbed methane gas. The sorption capacity of coal is mainly determined by the degree of maturity of the carbonized substance and the pressure, the value of which, in turn, is a function of the occurrence depth of the coal bed and is 0.8–0.9 of the hydrostatic pressure in coal fields.

The analysis, statistical processing, and generalization of the obtained results on sorption methane-bearing capacity and natural gas content were carried out in [18]. They are based on experimental data from many years of research on coal beds in Donbas with different degrees of metamorphism and at different depths. To estimate the gas content of coal, new indicators were proposed – the relative gradient of sorption methane-bearing capacity and the relative gradient of gas content, which allow comparing these characteristics measured in absolute values (cm^3/g, m^3/t) for individual coal beds of all grades of metamorphism, occurring in different geological conditions.

The relative gradient of sorption methane-bearing capacity of coal beds is the ratio of the next (for higher pressure) value of sorption methane-bearing capacity to the previous one (for lower pressure) with a step of 1 MPa. Similarly, the relative gradient of gas content of coal beds is the ratio of the next value of gas content to the previous one with the same step (1 MPa). The relative gradient of sorption methane-bearing capacity (gas content) is essentially a coefficient of decrease in sorption capacity (gas content) with depth, and accordingly, with increasing pressure, and is a non-dimensional quantity [18].

In work [18] it was proven that the sorption capacity of coal matter determines the natural regional (background) methane content of coal beds, and naturally, according to a hyperbolic dependence, decreases with increasing the occurrence depth and also naturally decreases in each of the depth intervals from low-metamorphosed (grade LF) coal to high-metamorphosed (grade A), with a relative gradient that asymptotically approaches 1 at pressures above 6 MPa.

The impact of a large number of factors on the natural gas content in coal beds makes it difficult to determine it for individual coal beds, which differ in various geological conditions. It is separately noted in [18] that against the background of general trends that form the natural regional background gas content, various deviations caused by various anomalies are superimposed. Anomalies can be different in nature. They can occur as a result of slow or sudden gas generation or the release of previously formed free methane. These can be positive anomalies (increase in gas content), which contribute to an increase in gas content and form gas accumulations and even cause gas-dynamic phenomena in coal mines. So are negative anomalies, which cause a decrease in gas content by lateral migration or degassing upward along the rise of rocks and subsequently from the Earth's surface into the atmosphere. To a large extent, tectonics and the hydrogeological regime determine local deviations of the quantitative content of gas in the coal-bearing strata from the regional background gas content of coal beds. The main task of the data and previous research [18] is to define the patterns of formation exactly of natural regional background gas content.

The values of relative gradients for coal of different grades naturally decrease with increasing the occurrence depth and also naturally decrease in each of the depth intervals from low-metamorphosed coal to high-metamorphosed coal. Quantitatively, the absolute gas content in coal beds of different degrees of coalification can vary within quite wide limits, but the nature of the change in the relative gradient of methane content is common to coal of all grades. A regular change in the relative gradient of methane content of coal beds is observed for the entire Donbas. At greater depths, the values of relative gradients for coal beds of all grades become equal. At depths of 300–400 m, the values of relative gradients are 1.07–1.12, at depths of 400–500 m - 1.04–1.07, and at depths of 500–600 m - 1.02–1.06. That is, the possible increase in gas content, with increasing depth, and accordingly pressure, can potentially be 2–6%, if the value of the relative gradient is equal to 1. This fully coincides with the data, according to which the increase in sorption in the pressure range of 5–10 MPa does not exceed 5–10%. [18]. Taking into account the pressures in the coal-bearing strata, which are usually equal to 0.8–0.9 hydrostatic, the main increase in gas content occurs at depths of 670–750 m (on average, about 700 m). Further growth in natural methane content should be expected to depths of 1100–1250 m, which corresponds to a pressure of 10 MPa, with subsequent stabilization.

According to the results of data approximation, the corresponding equations were obtained for each grade of coal metamorphism from gas to anthracite. The established empirical dependences of the gradients of relative methane content on the occurrence depth are polynomials of the third degree (or cubic polynomials). The general form of the curves is common for coals of different stages of metamorphism [18]. In essence, the dependences are a bundle of curves that asymptotically converge to unity.

Further generalization of the data and analysis of the results showed that the obtained dependences can best be characterized by a two-exponential model – formula 1. This formula is universal for determining the gradient of methane content in coal beds of different stages of metamorphism. The parameters of the two-exponential model are given in Table 1

$$q_H = 1 + a \cdot e^{-H \cdot b} + c \cdot e^{-H \cdot d}, \quad (1)$$

where q_H – the relative gradient of methane content for the predicted depth *H*, n/d; *H* – depth, m; *a, b, c, d* – empirical coefficients, n/d.

Table 1 – Parameters for calculating the relative gradient of the methane content for different coal grades

Coal grade	Indices $R°/V^{daf}$	q_{700}	*a*	*b*	*c*	*d*
G	0.50–1.00 / 33–46	1.03	13.998	0.0152	0.1429	0.0022
F	0.85–1.20 / 23–36	1.03	8.456	0.0165	0.2105	0.0030
C	1.21–1.60 / 18–20	1.02	2.001	0.0108	0.1825	0.0032
LC	1.30–1.90 / 14–22	1.02	2.057	0.0103	0.1316	0.0029
L	1.60–2.59 / 8–18	1.01	7.931	0.0224	0.5138	0.0058
A	≥2.60 / <8	1.02	1.698	0.0117	0.2698	0.0037

Note: in Table 1, the q_{700} is the relative gradient of methane content for a depth of 700 m (non-dimensional – n/d).

The appropriate graphs corresponding to the bi-exponential model of the dependence of the relative gradient on depth (*H*) are shown in Fig. 1. It is worth noting that the graphs for coal grades C and LC practically superimpose on one another (see Fig. 1).

This model fully and quantitatively confirms the previously made conclusion regarding the stabilization of gas content at depths of about 1200 m. Grounded on the dependence of the relative gradient of gas content on depth, according to the bi-exponential model, and extrapolating this dependence towards greater depths, it can be predicted that at depths of 1100–1200 m, the natural regional gas content of coal beds should be completely stabilized (Fig. 1).

Currently, there are three viewpoints on this issue. In line with most researchers, the increment of methane content has practically stopped, and it has almost stabilized at depths of 800 meters [19, 20]. Some researchers believe that it is not the methane content as a whole that has stabilized, but its increment [19]. There is also a viewpoint that below a certain depth, the methane content should begin to decrease. That is, the gas content of coal increases with depth, then stabilizes, and with increasing depth over 1000 m, it begins to decrease. This is explained by a decrease in the sorption capacity of coal with increasing temperature [19]. The authors of works [21, 22] concluded that the gas content of coal beds below the gas weathering zone increases, after which it stabilizes. Others [23] believed that an increase in the occurrence depth would lead to a corresponding constant increase in methane content due to an increase in the amount of free phase gas in coal.

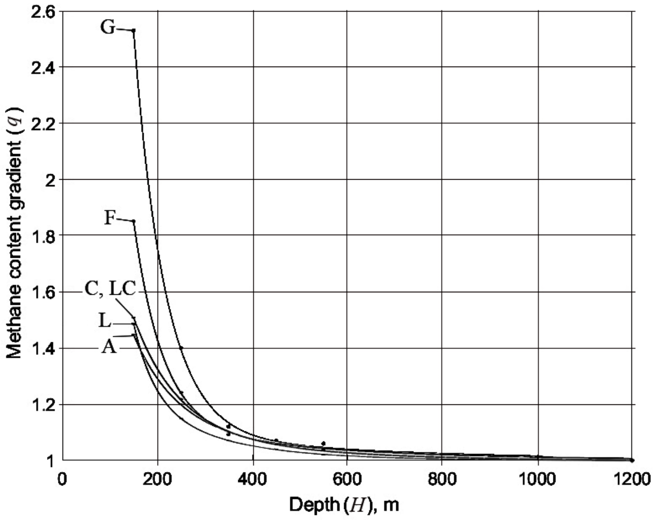

Figure 1 – Dependence of the relative methane content gradient in coal beds of different degrees of metamorphism on the depth

In work [19], we read the viewpoint of A.M. Bryzhanov and G.B. Yanovskaja that the change in methane content of coal beds corresponds to a hyperbolic dependence, i.e., initially, the methane content of coal beds increases sharply, but with depth, the rate of its growth begins to decrease, after which at depths up to 1700 m the methane content stabilizes. Later, V.Yu. Zabihailo and V.G. Nikolin [19] concluded that the stabilization of methane content should be attributed to the depth interval of 800–900 m, i.e., greater than that previously considered by other authors. Further, based on the dependencies that have been obtained from the literature data, the authors of the work [19] prove not the stabilization of methane content at great depths but the reaching of the maximum values, after which its decrease occurs. In mathematical essence, this is a parabola that opens downward, i.e., with a maximum at the top. In this case, the vertex of the parabola corresponds to the point where the function reaches its maximum value, after which the value of the function (i.e., methane content) decreases with a further increase in depth. Without overestimating the importance of statistical processing of actual data and realizing the conditional nature of any extrapolations, the authors [19] noted not an affirmative, but an acceptable nature of further decrease in methane content with depth. They indicated the limit for the beginning of this extrapolation at a depth of 1200 m, as the greatest, where at that time, the maximum methane content of coal was measured.

All other things being equal, a change in gas content, namely its decrease, can be expected with a temperature change. As is known, an increase in temperature reduces the sorption capacity of coal matter. Thus, there is information that the gas content of coal increases with depth, then stabilizes, and with an increase in depth above 1000 m begins to decrease [20].

The obtained dependences of the relative gas content gradient on depth and gas pressure for different grades of metamorphism can be used to develop a method for predicting the natural regional background gas content of coal beds by determining the limiting sorption capacity and calculating for the desired depth or pressure.

Unlike the previously known dependencies, which are purely statistical, the proposed new biexponential model has a physical background. It is based on the dependence of methane content on the sorption capacity of coal, which, in turn, is determined by pressure (and therefore depth). The sorption capacity increases rapidly in the section up to 6 MPa, and then slowly and slightly increases to 10 MPa, reaching its maximum at depths of about 1200 m – the limit (maximum potential gas-bearing capacity) for the corresponding degree of carbonization.

The principle of the method is that the natural methane content of coal beds is determined by their sorption capacity (methane-bearing capacity), which depends on the degree of carbonization (the coal grade [24]) and bed pressure (the occurrence depth) with correction for natural moisture and ash content. It should be assumed that the natural methane content of coal is mainly (by 90%) determined by its sorption volume, and the sorption volume reaches a maximum and stabilizes at pressures of 6 MPa. Based on the conclusion regarding the limiting value of the sorption capacity of coal, which is achieved at these pressures (over 6 MPa), one should expect a change in the natural gas content according to the dependence, with approach to the asymptote equal to 1. The saturation limit practically occurs at these pressures (6 MPa), and a further increase in pressure causes only a slight increase in sorption (the increase in sorption in the pressure range of 5–10 MPa does not exceed 5–10%).

The method includes drilling exploratory wells or researching mining workings, sampling coal, and determining the natural moisture and ash content by laboratory methods. The set task is solved by the fact that in the method for determining the natural methane content in coal beds from the selected samples and with laboratory tests, the yield of volatile substances V^{daf} and the reflectivity of vitrinite R° (which are used to determine the coal grade [24]) are defined. The limiting sorption capacity (methane-bearing capacity) of coal Q is also defined, and the relative methane capacity gradient q is calculated for the forecast depth H using the corresponding coefficients a, b, c, and d (see Table 1) by formula 1. The sorption volume (limiting sorption capacity) of hard coal is determined by known laboratory methods – the volumetric method or EPR spectroscopy method [17, 25].

The natural gas capacity of a coal bed for the required depth of the prediction, with correction for the coal bed moisture W and ash content Az, is calculated by the formula

$$X = \left(\frac{Q \cdot q_{700}}{q_H} \right) \cdot \left(\frac{100 - W - Az}{100} \right), \qquad (2)$$

where X – natural gas content of coal beds m^3/t; Q – limiting sorption capacity (methane-bearing capacity) of coal, m^3/t; q_{700} – the relative gradient of methane content for a depth of 700 m, non-dimensional (n/d); q_H – the relative gradient of methane content for the predicted depth, n/d; W – bed moisture of coal, %; A_z – ash content of coal, %.

The specified method enables us to determine the natural methane content of coal of varying degrees of metamorphism, taking into account their depth of occurrence.

This method for predicting the methane content of coal beds can be used at the stage of prospecting and evaluation and detailed exploration/geological-exploration works.

At the stage of prospecting and evaluation works, the total reserves of gas in coal beds, its distribution by depth, and the potential danger of gas release are assessed. The use of the proposed biexponential model allows estimating the regional background gas content without conducting detailed well tests.

At the stage of detailed exploration, the method can be used to determine the gas content of beds within specific mine fields or license areas. In this case, the method allows the assessment of possible risks in the future operation of mines, especially concerning the explosion hazard due to methane.

Thus, this method is useful at stages when the evaluation of natural methane content is required for further engineering of field development. An application for the patent for a utility model has been filed for the developed method.

4. Conclusions

For the previously established dependence of the relative gradient of methane content in coal beds on the depth of occurrence, a biexponential model is proposed, which is universal for determining the gradient of methane content in coal beds of different stages of metamorphism. The proposed new biexponential model has a physical background – it is based on the dependence of methane content on the sorption capacity of coal, which, in turn, is determined by pressure (and hence, by depth). In line with this model, the natural methane content of coal beds grows rapidly with increasing pressure to 6 MPa (depth 670–750 m), and then slowly and insignificantly (up to 10%), increases up to 10 MPa, reaching its maximum (maximum potential gas-bearing capacity) for the corresponding degree of carbonization of fossil organics at depths of about 1200 m, with subsequent stabilization.

The obtained dependences of the relative gradient of gas content on depth and gas pressure for different grades of metamorphism were used to develop a method for predicting the natural regional background gas content of coal beds by determining the limiting sorption capacity of coal. The method allows for determining the natural methane content of coal of different degrees of metamorphism, considering their depth of occurrence, with correction for moisture and ash content.

Conflict of interest

Authors state no conflict of interest.

REFERENCES

1. Kholod, N., Evans, M., Pilcher, R.C., Roshchanka, V., Ruiz, F., Cot, M. and Collings R. (2020), "Global methane emissions from coal mining to continue growing even with declining coal production", *Journal of Cleaner Production*, vol. 256, 120489, https://doi.org/10.1016/j.jclepro.2020.120489

2. Perera, M.S.A., Ronjith, P.G., Choi, S.K., Airey, D. and Weniger, P. (2012), "Estimation of Gas Adsorption Capacity in Coal: A Review and an Analytical Study", *International Journal of Coal Preparation and Utilization*, vol. 32, issue 1, pp. 25–55, http://doi org/10.1080/19392699.2011.614298

3. Jamiu, M. Ekundayo and Reza, Rezaee (2019), "Volumetric measurements of methane-coal adsorption and desorption isotherms – effects of equations of state and implication for initial gas reserves", *Energies*, vol. 12 (10), pp. 1–13, https://doi.org/10.3390/en12102022

4. Dameng, Gao, Lin, Hong, Jiren, Wang and Dan, Zheng (2019), "Adsorption simulation of methane on coals with different metamorphic grades", *AIP Advances*, vol. 9, 095108, https://doi.org/10.1063/1.5115457

5. Kui, Dong, Zhiwei, Zhai, and Aijun, Guo (2021), "Effects of Pore Parameters and Functional Groups in Coal on CO_2/CH_4 Adsorption", *ACS Omega,* vol. 6, pp. 32395‒32407, https://doi.org/10.1021/acsomega.1c02573

6. Kumar, Harinandan, Mishra, M.K. and Mishra, S. (2019), "Sorption capacity of Indian coal and its variation with rank parameters", *Journal of Petroleum Exploration and Production Technology*, vol. 9, pp. 2175–2184, https://doi.org/10.1007/s13202-019-0621-1

7. Okolo, Gregory, N., Everson, Raymond C., Hein, W.J.P. Neomagus, Sakurovs, Richard, Grigore, Mihaela and Bunt, John R. (2019), "Dataset on the carbon dioxide, methane and nitrogen high-pressure sorption properties of South African bituminous coals", *Elsevier*, vol. 25, pp. 40–53, https://doi.org/10.1016/j.dib.2019.104248

8. Raharjo, S., Bahagiarti S., Purwanto, H.S. and Rahmad, B. (2018), "The effect of coal petrology on the capacity of gas methane absorption in coal formation Tanjung Barito in Binuang Region, South Kalimantan", *Series: Earth and Environmental Science*, vol. 212, 012029, https://doi.org/10.1088/1755-1315/212/1/012029

9. Czerw, Katarzyna,·Dudzińska, Agnieszka, Baran, Paweł and Zarębska, Katarzyna (2019), "Sorption of carbon dioxide on the lithotypes of low rank coal", *Adsorption*, vol. 25, pp. 965–972, https://doi.org/10.1007/s10450-019-00122-5

10. Wojtacha-Rychter, Karolina, Howaniec, Natalia and Smoliński, Adam (2020), "Effect of porous structure of coal on propylene adsorption from gas mixtures", *Scientific reports*, vjl. 10, p. 11277, https://doi.org/10.1038/s41598-020-67472-x

11. Skoczylas, N., Dutka, B. and Sobczyk, J. (2014), "Mechanical and gaseous properties of coal briquettes in terms of outburst risk", *Fuel*, vol. 134, pp. 45–52, https://doi.org/10.1016/j.fuel.2014.05.037

12. Zhai, C., Xiang, X., Xu, J. and Wu, S. (2016), "The characteristics and main influencing factors affecting coal and gas outbursts in Chinese Pingdingshan mining region", *Natural Hazards*, vol. 82, no. 1, pp. 507–530, https://doi.org/10.1007/s11069-016-2195-2

13. ASTM International (2010), *ASTM D 7569-0: Standard practice for determination of gas content of coal — direct desorption method*, West Conshohocken, Pennsylvania, USA.

14. Standards Association of Australia (1999), *AS 3980-1999: Guide to the determination of gas content of coal seams. Direct desorption method,* Standards Association of Australia, Dover Publishing 1999 North Sydney, Australia.

15. McLennan, J. D., Schafer, P. S. and Pratt T. J. A (1995), *Guide to Determining Coalbed Gas, Gas Research Institute Report GRI-94/0396,* Chicago, Illinois, USA.

16. Imgrund, T. and Bauer, F. (2013), *Relaxation and gas drainage boreholes for high performance longwall operations in low permeability coal seams. Mining Report*, 149 pp. 159–166, https://doi.org/10.1002/mire.201300019

17. *Catalog of reservoir properties of coals and anthracites of the Donets and Lviv-Volyn basins* (1988), MaкNII, Makeyevka, USSR.

18. Bezruchko, K.A., Burchak, O.V., Pymonenko, L.I. and Chelkan, V.V. (2024), "Sorption capacity and natural gas content of coal beds of Donbas", *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, vol. 4, pp. 18–26, https://doi.org/10.33271/nvngu/2024-4/018

19. Zabihailo, V.Yu. and Nikolin, V.I. (1990), *Vliyanie katageneza gornyh porod i metamorfizma uglej na ih vybrosoopasnost*, [The influence of catagenesis of rocks and metamorphism of coals on their outburst hazard], Naukova dumka, Kiev, USSR.

20. Bulat, A.F., Lukinov, V.V. and Bezruchko, K.A. (2017), *Umovy formuvannia hazovykh pastok u vuhlenosnykh vidkladakh*, [Conditions of gas traps forming in carboniferous sediments], Naukova Dumka, Kyiv, Ukrainian, ISBN 978-966-00-1534-0.

21. Zabihailo, V.Yu. and Shyrokov, O.Z. (1972), *Problemy geologii gazov ugolnykh mestorozhdeniy*, [Problems of Geology of Coal Deposit Gases], Naukova dumka, Kiev, USSR.

22. Zabihailo, V.Yu., Lukinov, V.V. and Shyrokov, O.Z. (1983), *Vybrosoopasnost gornykh porod Donbassa*, [Outburst hazard of Donbas rocks], Naukova dumka, Kiev, USSR.

23. Olkhovychenko, A.E, Ivanov, B.M., Zubarev Yu.P. Galazov, R.O., Hainutdinov, S.A., Novoderezhkyn, O.P. and Ponomarov, I.F., (1988*), Prognoz vybrosoopasnosti ugolnykh plastov i gornykh porod pri razvedke i dorazvedke mestorozhdeniy*, [Forecast of outburst hazard of coal beds and rocks during exploration and further exploration of deposits], Tehnika, Kiev, USSR.

24. DP UkrNDNC (2015), *DSTU 3472:2015 Vugillya bure, kamyane ta antratsyt. Klasyfikatsiya* [DSTU 3472:2015 Brown coals, Hard coals and Anthracite. Classification], DP UkrNDNC, Kyiv, Ukraine.

25. Antsiferov, A.V., Tirkel, M.G., Khokhlov, M.T., Privalov, V.O., Golubev, O.A., Maiboroda, A.O. and Antsyferov, V.A. (2004), *Gazonosnost ugolnykh mestorozhdeniy Donbassa* [Gas content of coal deposits in Donbas], in Azarov, N.Ya. (ed.), Naukova dumka, Kyiv, Ukraine.

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ДВОЕКСПОНЕНЦІЙНА МОДЕЛЬ ПРОГНОЗУ ПРИРОДНОЇ РЕГІОНАЛЬНОЇ ГАЗОНОСНОСТІ ВУГІЛЬНИХ ПЛАСТІВ

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Анотація. Метан є потужним парниковим газом. Метан - основний компонент газів вугільних родовищ, і оскільки майже уся вугленосна товща гірських порід насичена метаном, видобуток вугілля на вугільних шахтах в процесі їх експлуатації і після завершення проведення очисних робіт постійно супроводжується виділенням метану у вироблений простір. За прогнозами його викиди до 2100 року з діючих підземних виробок кількісно збільшуться в 4 рази, а викиди із закритих шахт збільшуться в 8 разів. Тому прогноз його емісії в атмосферу на засадах оцінки газоносності вугільних пластів є актуальним сучасним завданням та не втратить своєї актуальності у майбутньому.

Метою роботи була розробка нового методу прогнозу метаноносності вугільних пластів для вугілля різних марок відповідно до глибини залягання.

Для встановленої раніше залежності відносного градієнту метаноносності вугільних пластів від глибини залягання запропонована двоекспоненційна модель, яка є універсальною для визначення градієнту метаноносності вугільних пластів різних стадій метаморфізму. Нова двоекспоненційна модель має фізичне підґрунтя – вона базується на залежності метаноносності від сорбційної здатності вугілля, яка, своєю чергою, визначається тиском (глибиною). За цією моделлю природна метаноносність швидко зростає зі збільшенням тиску до 6 МПа, а потім повільно й незначною мірою, збільшується до 10 МПа, досягаючи свого максимуму (максимальної потенційної газоємності) для відповідного ступеня вуглефікації на глибинах близько 1200 м), з подальшою стабілізацією. Отримані залежності відносного градієнту газоносності від глибини та газового тиску для різних марок метаморфізму використані для розробки методу прогнозування природної регіональної фонової газоносності вугільних пластів, шляхом визначення граничної сорбційної здатності вугілля. Спосіб дозволяє визначати природну метаноносність кам'яного вугілля різного ступеня метаморфізму, з урахуванням глибини залягання, з поправкою на вологість та зольність.

Ключові слова: Донбас, вугільні пласти, природна газоносність, сорбційна ємність.