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The outburst probability index (Ww) as a new tool in the coal seam outburst hazard forecasting

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Gas and rock outbursts are one of the most unpredictable natural hazards in Polish and worldwide underground mining. The complexity and unpredictability of this phenomenon make forecasting and underground prevention difficult to achieve. Gas-geodynamic phenomenon occurs in greater intensity in the southern part of the Upper Silesian Coal Basin (USCB) – close to the Bzie-Czechowice fault zone. The relatively low firmness of coal combined with high methane content and pressure may result in a coal seam outburst. To forecast the gas and rock outburst occurrence, the sorption capacity and gas diffusion parameters are used in Polish coal mining. To provide a new, more direct and helpful tool for outburst hazard occurrence interpretation – an outburst probability index (Ww) has been developed in the CLP-B Laboratory. The components of the simple formula are: methane content, firmness of coal, desorption intensity, effective diffusion coefficient and methane sorption capacity. The four numerical ranges are provided to define the probability of the coal seam outburst occurrence. The new method proposed by the CLP-B Laboratory simplifies the outburst hazard prediction and can be used successfully in the coal mines to foresee the forthcoming danger. The result of the outburst probability index reflects changes in each component, which makes it adequate in long-term outburst research in the new drifting roadways.

Keywords

gas and rock outburst, methane content, natural hazards, methane sorption capacity, gas diffusion.

The Outburst Probability Index (*Ww*) as a New Tool in the Coal Seam Outburst Hazard Forecasting

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Abstract

Gas and rock outbursts are one of the most unpredictable natural hazards in Polish and worldwide underground mining. The complexity and unpredictability of this phenomenon make forecasting and underground prevention difficult to achieve. Gas-geodynamic phenomenon occurs in greater intensity in the southern part of the Upper Silesian Coal Basin (USCB) − close to the Bzie-Czechowice fault zone. The relatively low firmness of coal combined with high methane content and pressure may result in a coal seam outburst. To forecast the gas and rock outburst occurrence, the sorption capacity and gas diffusion parameters are used in Polish coal mining. To provide a new, more direct and helpful tool for outburst hazard occurrence interpretation − an outburst probability index (*Ww*) has been developed in the CLP-B Laboratory. The components of the simple formula are: methane content, firmness of coal, desorption intensity, effective diffusion coefficient and methane sorption capacity. The four numerical ranges are provided to define the probability of the coal seam outburst occurrence. The new method proposed by the CLP-B Laboratory simplifies the outburst hazard prediction and can be used successfully in the coal mines to foresee the forthcoming danger. The result of the outburst probability index reflects changes in each component, which makes it adequate in long-term outburst research in the new drifting roadways.

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1. Introduction

The gas and rock outburst phenomenon is one of the most dangerous natural hazards that is present in coal, salt and ore underground mining [1−4]. A gas-geodynamic event is a result of several geological factors like high rock gas pressure (methane, carbon dioxide, etc.), high rock gas content and occurrence of weakened zones (low rock firmness, tectonics, etc.) [e.g. 5]. The prediction of the gas-induced geodynamic events in Polish mining is based on the outburst indicators measured during mining and in the laboratory. Additional parameters − coal sorption properties (methane sorption capacity and effective coefficient of methane diffusion in coal) are determined by mining specialists [2,6]. Prediction and risk analysis of the outburst occurrence is mostly based on the firmness of coal, gas desorption intensity, gas content and pressure. There were many equation methods and dependences between outburst indicators developed in the Polish and world mining [5,7−10]. The CLP-B Laboratory measures coal sorption properties in the hazards zones, during drifting of new roadways, according to Polish regulation [6]. Mining at greater depths, in the fault zone vicinities and in the unrecognized mining areas is associated with the natural hazards intensification [11−13]. There was an urgent need to develop and apply a new solution to better interpret outburst parameters and sorption properties combined with forecasting the gas-induced geodynamic events better. The novelty of the outburst probability index (*Ww*) is the danger assessment included in one simple equation, which can be used by mining specialists, scientists and mining technicians. Most of the equation components are studied even a few times a week, which is why the outburst risk changes can be seen during mining. The coal seam outbursts, which occurred in the world

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mining, were connected with fault tectonics. The altered zone presence is associated with e.g. changed stress and gas distribution in the coal seam [1,9–13]. The most violent gas-geodynamic events which took place in the Upper Silesia Coal Basin (USCB) (Pniówek coal mine in 2002 – no deaths, 55,000 m^3 of released CH_4 and Zofiówka coal mine in 2005–15,000 m^3 CH_4, three deaths) were associated with tectonic disturbances [9–12]. Coal was sheared, changed and weakened, which has helped methane to accumulate. An outburst took place also in the homogenous seam without tectonic disturbances (Budryk coal mine in 2012–340 m^3 of CH_4 was released, and no fault was documented) [9].

2. Materials and methods

The CLP-B Laboratory performs sorption capacity and effective diffusion coefficient tests on hard coals to characterise their capability of gas (methane) accumulation and desorption. Tests are conducted on high-accuracy gravimetric analysers – IGA 001 and XEMIS 001. The new tool – the outburst probability index (*Ww*), has been developed on the basis of the analysis of 350 samples (sorption and diffusion) and accompanying gas-geodynamic data (coal firmness, desorption, gas content). A coal seam outburst is a violent gas and coal release to the mine workings as a result of gas pressure and content, stress regime and faults and breaks presence in the rock mass [13,14]. In the Authors' opinion, the outburst interpretation and prediction should contain fault tectonics as one of the main elements to study and recognise. Most of the gas-induced geodynamic events are related to fault tectonics (from a few centimetres to a few meters drop) [7,10–16]. Faults often cause deformation in the coal structure, which favours the gas (methane) accumulation in the changed (altered) cataclastic or mylonitic coal grains under high pressure [e.g. 16]. Coals in the close vicinity of the tectonic zones are often characterised by lower firmness and greater gas diffusion and desorption [e.g. 11, 15, 16]. In the USCB, most of the gas and rock outbursts took place in the area close to the Bzie-Czechowice fault zone [e.g. 1, 13]. The outburst probability index and comprehensive research of tectonics need to complement each other during gas-related hazard predictions.

Sorption and diffusion long-term tests were performed in the isothermal (in the rock mass temperatures) and isobaric conditions on all types of hard coals produced in the gas and outburst hazard zones in the Polish mining [17,18]. The additional tests of altered coals from tectonic zones were made to compare results with non-altered coals (in $50 \times$ magnification). To develop the formula and result ranges of the outburst probability index (*Ww*), the limit values of the accompanying gas-geodynamic data and sorption properties were defined, based on the Regulation of the Minister of Energy [6].

- The coal firmness describes the rock's (coal's) ability to resist damage, and in Polish mining, $f = 0.30$ is the critical value [6,19].
- The methane desorption describes the intensity of realising gas from crushed coal sample after 2 min. The test is performed in a liquid manometer – DMC 2. The critical value is 1.20 kPa [6,10,20].
- The gas (methane) content is considered the most important outburst factor by many scholars [e.g. 5, 7]. It shows the amount of adsorbed methane in 1 Mg of dry ash-free (*daf*) coal substance. The critical methane content was set at 4.5 and 8.0 m^3/Mg^{daf} [e.g. 11, 12, 20].
- The sorption capacity is defined as the volume of sorbed gas (CH_4) on a dry coal sample at a given temperature and pressure, expressed in cm^3/g or m^3/Mg [2,10,21]. The critical value defining a poorly sorbed coal, was determined in the CLP-B Laboratory as 1.50 cm^3/g.
- The effective diffusion coefficient (defined by Timofeev [22]) measured as methane molecule's movement in solid rock (coal) between grains given in cm^2/s [21,23]. After Wierzbiński [10], the outburst-prone coal is defined when diffusion coefficient is measured greater than 0.15×10^{-8} cm^2/s. The faster molecule's movement is caused by a damaged coal structure. Close to the geological disturbances, the sorption kinetics is characterised by relatively big values $De > 0.8 \times 10^{-8}$ cm^2/s [10].

Table 1. Categories of the gas and rock outburst hazard [6].

Number of category	Methane content [m^3/Mg^{daf}]	Coal firmness	Desorption intensity [kPa]
I	4.5–8.0	< 0.3	> 1.20
II	> 8.0		
III	• Gas and rock outburst occurred • Sudden methane leakage occurred • II category conditions and extra outburst symptoms need to occur [6]		

In Polish hard coal mining, three categories of gas and rock outburst hazards are obligatory [6] (Table 1). For classifying a coal seam or part of it as one of the three categories, the methane content is used as the primary condition. The second one is coal firmness or desorption intensity results or additional conditions like gas-related phenomena in the past.

3. Results and discussion

3.1. Outburst probability index formula

An outburst probability index has been developed a simple equation (1) for mining authorities to interpret five main outburst components together. The novelty in the conducted research was taken into consideration the sorption capacity and diffusion as equally important values as firmness, desorption and gas content.

$$Ww = \frac{G \times De \times dp}{(1+f)a_1} \quad (1)$$

where:

G – gas (methane content) [m^3/Mg],
De – effective diffusion coefficient [cm^2/s],
dp – methane desorption intensity [kPa],
f – firmness,
a_1 – sorption capacity [m^3/Mg].

The result of equation (1) is a dimensionless value ≥ 0. Solving the equation on the basis of the limit values of the accompanying gas-geodynamic data and sorption properties (see section 2), the result received for the I and II categories of methane hazard is 4.2 and 7.4, respectively. These two results were determinants for the categorization of the Ww (Table 2).

The result of the outburst probability index reflects changes in each component what makes it adequate in long term outburst research in the new drifting roadways. The sorption capacity and diffusion coefficient define the gas in the equilibrium state, the amount of free gas and its dynamic transportation in the system of the pores in coal during liberation processes [e.g. 9, 24]. All tested coals (500) were sampled in the gas and outburst hazards areas. The coal firmness ranged from 0.31 to 0.58, desorption intensity from 0.10 to 1.96 kPa, and methane content from 0.5 to > 9 m^3/Mg^{daf}. The sorption properties of coal are reduced with the increase of rock mass temperature by about 0.5–0.8 m^3/Mg/1°C [17,21]. Besides temperature, sorption properties are associated with maceral composition, metamorphism stage, moisture, ash content and pressure [e.g. 21]. The average sorption capacity from 500 coal samples was 2.15 m^3/Mg (from < 1.5 to > 3.0 m^3/Mg), and the diffusion coefficient ranged from 0.02 to 0.34×10^{-8} cm^2/s. The Langmuir sorption isotherms varied from 11 to 25 m^3/Mg (Figure 1), which shows the varied properties of coals – from limited to large sorption capacities. The large spread of the data makes correct outburst interpretation difficult to achieve. The outburst probability index includes all the necessary variables; therefore, hazard categorization helps to identify the potential risk of the gas-related phenomenon. The average result of the Ww was 1.4, which points to a medium probability of most of the studied coal seams. The highest probabilities were found for the close vicinities of tectonic zones ($Ww > 7$), where diffusion and desorption were increased, but gas content was relatively low ($G <$ 4.5 m^3/Mg^{daf}), which suggests the degassing act of the faults.

Table 2. Categories of the outburst probability index results [own research].

Result of the Ww equation (1)	The outburst risk probability
< 1	low
1–4	medium
4–7	high
> 7	extremely high

3.2. Altered coals from tectonic zones

Coals from the areas of tectonic disturbances were studied to identify the altered structure – cataclasis. On the other hand, a sample from a further distance from the fault was studied to compare all the outburst indicators together. The magnification was × 50 (Figure 2). In the mining history, most of the outbursts took place in the areas of geological disturbances [17,20]. Coals found in the post-outburst material are often characterized by lower strength parameters. They can adsorb much more gas than coals in the undisturbed rock mass area, and the diffusion is higher than average [e.g. 15]. In Figure 2a, the altered coal with cataclastic structure is presented. The effective diffusion coefficient (0.34×10^{-8} cm^2/s) combined with extremely low coal strength ($f = 0.30$–0.31) and good sorption properties (> 2 m^3/Mg) resulted in Ww > 7, which classifies that coal to extremely prone to outburst phenomenon. The degassed zone in the close area to the disturbance lowered the overall Ww score, but it shows the usefulness of the outburst probability index for effective interpretation and prediction of the gas and rock outburst under similar conditions in the future. Further from the fault, the gas content of the coal seam was varied from 2.5 to

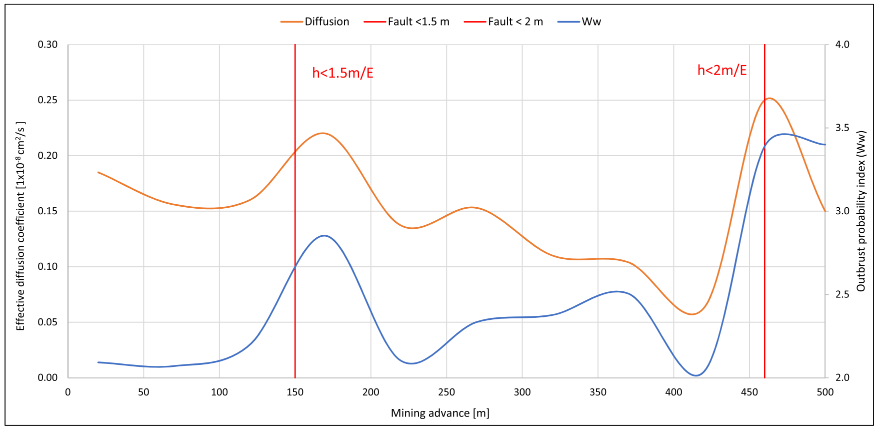
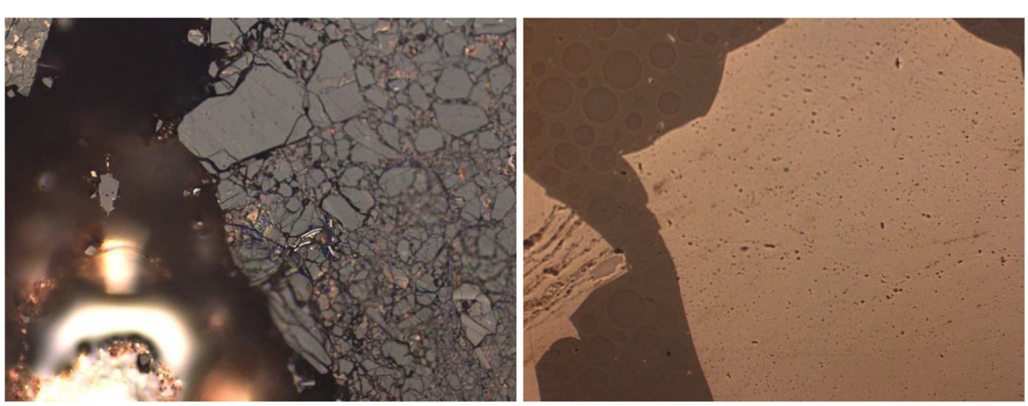


Fig. 1. The minimum and maximum Langmuir's sorption of tested coals [own research].

6.0 m^3/Mg^{daf}, which points to unequal coal seam saturation. Firmness and diffusion were, on average, at a safe level according to [6], but diffusion slightly exceeded 0.15–0.20 $\times 10^{-8}$ cm^2/s in some parts of the seam. The coal structure was solid and unaltered (Figure 2b), which resulted in *Ww* 1.0–2.5 – which means a medium probability of gas-geodynamic events. In the Author's opinion, based on the performed research, methane content is not the primary indicator in the outburst hazard forecasting. In one of the studied excavations, the methane content oscillated from 6 to > 9 $m^3/Mg^{daf,}$ and methane desorption was always > 1.20 kPa. Therefore, the *Ww* results varied from 1.5 to 3.0, which means that the risk of the outbursts was just medium. The rest of the outburst indicators have lowered the overall risk (f > 0.45; a_1 > 2 m^3/Mg and $De <$ 0.05 $\times 10^{-8}$ cm^2/s). This means that even very high methane content combined with exceeded desorption is not always identified with outburst-prone coals. During the drifting of all studied excavations, no methane-related phenomenon was observed.

3.3. The gas-related hazard interpretation and prediction

The outburst probability index *Ww*, as a new tool in gas and rock outburst interpretation, needs to be completed by tectonic analyses. Geological disturbances may act as "gas traps" for migrating methane, magnifying the methane emission and outburst hazard [e.g. 7, 25]. Additionally, in the Upper Silesian Coal Basin, the coal permeability is poor, often below 1 mD. Thus, methane accumulated under relatively big pressure is not easy to gain from coal seams by the underground degassing, which increases the gas and rock outburst hazard [17]. Fault tectonics may weaken the coal and surrounding rocks' structure and accumulate the free gas in pores and breaks under relatively big pressure [e.g. 3, 26, 27]. The structurally changed coals (cataclastic) are able to accumulate more methane than non-changed coals [e.g. 27]. When there are no prevention works, blasting or mining by roadheaders may release all accumulated energy



a b

Fig. 2. The microscopic photos of altered (a) and non-altered (b) coals [own research].

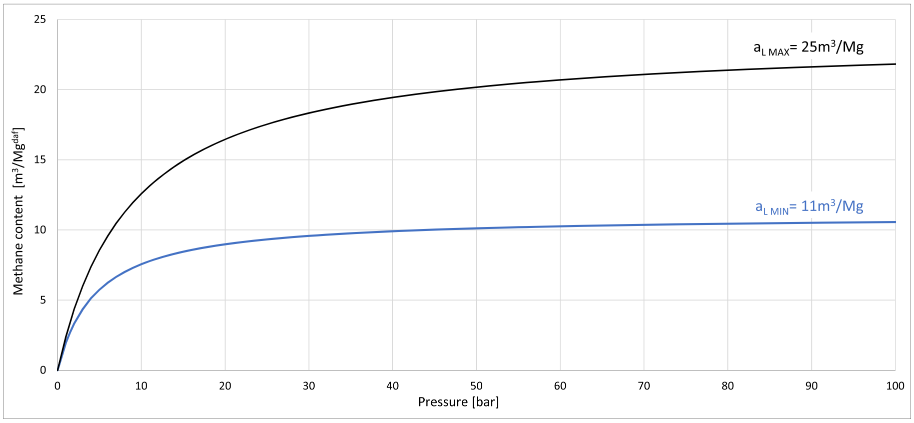


Fig. 3. The effective diffusion coefficient and outburst probability index changes during mining in one of the excavations [own research].

and initiate a coal seam outburst. The accurate identification and analysis of any disturbance in the vicinity of drifting excavation need to be a part of proper coal seam outburst hazard forecasting. Even relatively small faults may increase the outburst hazard, which was seen in one of the tested galleries (Figure 3), where the diffusion coefficient suddenly increased near the occurrence of the faults. Simultaneously, the *Ww* index values have increased too, which was caused by lowered coal firmness and greater diffusion coefficient. In the *Ww* index equation, those values deterioration resulted in bigger *Ww* outcomes – over 2.5 close smaller fault (1.5 m drop) and 3.5 close to larger dislocation (2 m drop), respectively (Figure 3). The overall hazard tested as *Ww*, showed similar outcomes in the close vicinity to tectonic disturbance during mining. Due to tectonic disturbances, coal firmness may be lowered and altered coal structure can be favourable to the liberation greater volumes of methane from coal. The series of laboratory and in-situ tests show that the regional and local fault zones need to be recognized and documented as soon as possible to prevent the coal seam gas-induced hazards.

4. Conclusions

The coal seam outburst phenomenon is one of the most dangerous and unpredictable natural hazard in Polish and world underground mining. The gas-geodynamic event is caused by many factors which work simultaneously. The geological disturbances may weaken the coal structure, which can be the cause of greater amounts of the free methane accumulation. The outburst indicators (e.g. firmness, desorption) are measured during mining and in the laboratory (sorption properties). The wide range of results makes the gas-induced hazard hard and complex to predict. In the CLP-B Laboratory, the outburst probability index (*Ww*) was performed to interpret five main outburst components together. The outburst risk probability ranges from low (< 1) to extremely high (> 7). During tests, 500 coal samples were examined and interpreted to perform four categories of the risk probability. The sorption capacity, diffusion coefficient, firmness, methane content and desorption are included in the simple equation to make the outburst indicators easier to interpret and predict gas-induced phenomenon. The newly developed index shows the outburst risk changes during mining, which is not effortless based on single, separate data. The outburst probability index (*Ww*) can be used successfully in the coal seam outburst hazard areas to foresee the forthcoming peril. The application of new tools is an urgent need to fight and prevent the gas and rock outburst in the underground coal mines. The new method – the outburst probability index (*Ww*) – proposed by the CLP-B Laboratory simplifies the outburst hazard foresee and can be used successfully in the coal mines to forecast the gas-inducted hazard. The result of the outburst probability index reflects changes in each component, which makes it applicable in long-term outburst research in the new drifting galleries.

Ethical statement

The authors declare no ethical issue.

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Conflicts of interest

The authors declare no conflict of interest.

RESEARCH ARTICLE

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References

[1] Dutka B, Wierzbicki M. Wybrane własności węgli w rejonach zagrożonych wyrzutami metanu i skał [some properties of outburst prone coals in upper silesian Coal Basin, Poland]. Gornictwo i geoinżynieria. Rok 32. Zeszyt 1. 2008.
[2] Koptoń H. Alternative methodology to determine effective coefficient of methane diffusion in coal. J Sustain Mining 2020;19(2). Article 3.
[3] Baryakh AA, Andreiko SS, Fedoseev AK. Gas-dynamic roof fall during the potash deposits development. J Mining Inst 2003;246:601−9.
[4] Kozieł K, Nowakowski A, Sitek L, Skoczylas N. Rock and gas outbursts in copper mines: use of Brazilian tests to evaluate the work of disintegration of rock resulting from stresses produced by gas present in its porous structure. Rock Mech Rock Eng 2022;55:6209−25.
[5] Shi X, Song D, Qian Z. Classification on coal seam outburst hazards and evaluation of the importance of influencing factors. Open Geosci 2017;9:295−301.
[6] Regulation of the minister of energy on detailed requirements for the operation of underground mining facilities. 2016. Retrieved from, http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20170001118/O/D20171118.pdf. [Accessed 1 October 2022].
[7] Song W, Zhang H. Regional prediction of coal and gas outburst hazards based on multifactor pattern recognition. Proc Earth Planetary Sci 2009;1:347−53.
[8] Skoczylas N. Koncepcja wspomagania analizy ryzyka za pomocą logiki rozmytej na przykładzie zagrożenia wyrzutowego w kopalni węgla kamiennego. Górnictwo i Geoinżynieria 2008;32:1.
[9] Skoczylas N, Pajdak A, Kozieł K, Teixeira L. Methane emission during gas and rock outburst on the basis of the unipore model. Energies 2019;12.
[10] Wierzbiński K. Zagrożenie wyrzutami gazów i skał. In: Konopko W [red.] Bezpieczeństwo pracy w kopalniach węgla kamiennego. Tom 2. GIG, Katowice; 2013.
[11] Kędzior S, Dreger M. Methane occurrence, emissions and hazards in the upper silesian Coal Basin, Poland. Int J Coal Geol 2019;211:103226.
[12] Dreger M, Kędzior S. Methane emissions against the background of natural and mining conditions in the Budryk and Pniówek mines in the upper silesian Coal Basin (Poland). Environ Earth Sci 2021;80:746.
[13] Dutka B. Effect of depth on the sorption capacity of coals affected by outburst hazard. Fuel 2021;306:121611.
[14] Hyman DM. A review of the mechanisms of gas outbursts in coal. Bureau of Mines Information Circular. United States Department of the Interior; 1987.
[15] Lama RD, Bodziony J. Management of outburst in underground coal mines. Int J Coal Geol 1998;35:83−115.
[16] Cao Y, He D, Glick DC. Coal and gas outbursts in footwalls of reverse faults. Int J Coal Geol 2001;48:47−63.
[17] Kędzior S, Dreger M. Geological and mining factors controlling the current methane conditions in the Rydułtowy coal mine (upper silesian Coal Basin, Poland). Energies 2022; 15:6364. https://doi.org/10.3390/en15176364.
[18] Cybulski K, Malich B, Wieczorek A. Evaluation of the effectiveness of coal and mine dust wetting. J Sustain Mining 2015;14(Issue 2):83−92.
[19] Wang C, Cheng Y, Yi M, Lei Y, He X. Powder mass of coal after impact crushing: a new fractal-theory-based index to evaluate rock firmness. Rock Mech Rock Eng 2020;53:4251−70.
[20] Li P, Cao Y, Li X, Wang F, Sun Z, Chen D, et al. Desorption characterization of methane in coal with different moisture contents and its influence on outburst prediction. Adv Civ Eng 2021;10.
[21] Wierzbicki M. Changes in the sorption/diffusion kinetics of a coal-methane system caused by different temperatures and pressures. Gospod Surowcami Miner 2013;29/4.
[22] Timofeev DP. Adsorption kinetic. Leipzigvol. 335; 1967.
[23] Kärger J, Ruthven DM. Diffusion in zeolites and other microporous solids. New York: Wiley & Sons; 1992.
[24] An F, Yuan Y, Chen X, Li Z, Li L. Expansion Energy of coal gas for the initiation of coal and gas outbursts. Fuel 2019;235: 551−7.
[25] Noack K. Control of gas emissions in underground coal mines. Int J Coal Geol 1998;35:57−82.
[26] Młynarczuk M, Wierzbicki M. Stereological and profilometry methods in detection of structural deformations in coal samples collected from the rock and outburst zone in the "Zofiówka" Colliery. Arch Min Sci 2009;54:189−201.
[27] Godyń K. Structurally altered hard coal in the areas of tectonic disturbances − an initial attempt at classification. Arch Min Sci 2016;61(3):677−94.