GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT
2016 Volume 32 Issue 2 Pages 153–174
DOI 10.1515/gospo-2016-0017

NORBERT SKOCZYLAS*

Fast evaluation of the coalbed methane content of coal viewed as an element leading to improvement in exploitation conditions

Introduction

Methane occurring in coal is both a huge depository of precious fuel – and a considerable hazard when it comes to exploitation of coal seams. Regardless of how we treat the coal-methane system – as a reserve of co-existing energetic raw materials, or, focusing on methane itself, as a troublesome co-occurring compound influencing the safety of exploitation – thorough knowledge of methane content is a starting point when it comes to balancing and describing a given coal seam, in conducting safe exploitation – with methane hazards and methane and rock outburst hazards in mind (Skoczylas 2014) – as well as in less common procedures, such as coal seam fracturing and methane extraction, or storing carbon dioxide in off-balance coal seams (Dutka et al. 2013).

The exploitation problems resulting from the presence of methane in coal may be a serious obstacle when it comes to increasing or maintaining the production capacities of hard coal mines. The coal and rock outburst hazard concerns, most frequently, the stage of the preparatory mining activities. Not so long ago, due to this type of hazard, all the mines of the Lower Silesian Coal Basin – where over 1,700 outbursts occurred – were liquidated and closed. The methane hazard usually becomes evident during the exploitation (?) of coal seams. Methane outbursts often result in casualties (as in the following hard coal mines:

---

* Ph.D., The Strata Mechanics Research Institute of the Polish Academy of Sciences, Kraków;
e-mail: skoczyla@img-pan.krakow.pl

Halemba 2006; Borynia 2008; Wujek-Ruch Śląsk 2009; Mysłowice-Wesoła 2014). Exploiting coal seams in such conditions entails huge financial expenses connected with outburst prevention, and decides about the speed with which mining activities are carried out. Thus, it becomes necessary to obtain thorough and up-to-date information about the parameters of the coal-methane system, determining the probability of the methane and outburst hazards, so that effective prevention measures could be introduced at the right time, ensuring work safety and reducing financial expenses.

The coalbed methane content and the desorbometric paramaters used in evaluating the methane content in coal are measured using samples constituted by bore dust, collected during drilling exploratory boreholes (PN G-44200:2013). In the case of such samples, it needs to be assumed that the release of methane from grains occurs as part of the desorption and diffusion processes (Wierzbicki 2013; Skoczylas 2015). The desorption process itself, understood as a change in the number of degrees of freedom of gas molecules, is instantaneous (Gawor and Skoczylas 2014), and all the temporal aspects of methane release concern the transportation of methane described by means of diffusion. The kinetics of methane released from coal – apart from the effective diffusion coefficient, which, in stable thermodynamic conditions depends on the structure of the coal matrix – is also determined by the size of the grain fraction used in the analysis. The proper selection of the grain fraction can facilitate the process of fulfilling the desired metrological objective. If the measurement coalbed methane content consists of multiple stages and the coal grains are ground during the process, the original size of grains should be large enough to ensure minimal methane losses between the separation of coal from the rock mass and placing it in the research container. If the measurement involves registering the process of methane release from coal grains within a specified time period, the size of the grains should be a compromise between the speed with which the release occurs – making it possible to register an observable part of the release process in a short period of time – and minimizing the susceptibility of the measurement method to uncertainties resulting from deviating from the time regime. In order to observe the full course of methane release from a coal sample, one needs to use a low grain fraction, so the process could reach the value approximate to the asymptotic value, in a relatively short time period.

1. Methane diffusion from coal

In the case of granular coal samples representing a small grain fraction, one can assume that the methane release from coal is, in fact, the process of diffusion of the desorbing gas, described by Fick's second law, which takes the sorption factor into account, linear in relation to pressure (Henry's isotherm):

$$\frac{\partial c(r,t)}{\partial t} = \frac{D}{1+\Gamma}\nabla^2 c(r,t) = D_e \nabla^2 c(r,t), D_e = \frac{D}{1+\Gamma} \tag{1}$$

An analytical solution to the equation (1) is possible only as development into the series (2) (Crank 1975; Timofiejew 1967):

$$m(t) = \frac{6M}{\pi^2}\left(\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2 D_e t}{R^2}\right)\right) \tag{2}$$

D_e – is the effective diffusion coefficient [cm^2/s],
M – is the total mass of gas released during the process [g],
$m(t)$ – is the mass of gas deposited in the moment t [g],
R – is the substitute grain radius – for a coal sample representing the $d_1 - d_2$ grain fraction [cm],
d_2 – determined from the formula , where d_1 and d_2 are the boundaries of the size of grains of the analyzed fraction.

At the initial stage of methane release, its kinetics are accurately described by the radical relation (3) (Pillalamarry et al. 2011).

$$m(t) = 6\sqrt{\frac{D_e \cdot t}{\pi \cdot R^2}} \tag{3}$$

In the case of conducting desorbometric observations, during which the release of methane to the pressure value observed within the excavation occurs, the asymptotic value *M* (2) is the so-called desorbable methane content *DMC*. If methane is released to a vacuum, the *M* value is the coalbed methane content *MC* reduced by the free gas *FG* representing methane in the coal pores, which is not bonded in a sorptive way.

From the perspective of conducting observations of methane release from a coal sample, a significant parameter which we are able to determine is the substitute grain radius in the second power of the denominator of the exponent of the exponential (2). Depending on the selection of the grain fraction, we can influence the time necessary for reaching the value approximate to the asymptotic value.

2. The coalbed methane content, the desorption intensity index, and the desorbable methane content

In the Polish hard coal mining industry, the coalbed methane content *Mn* is determined by means of the bore dust method described in the standard (PN-G 44200:2013). The grain fraction of the bore dust from boreholes is 1.0–2.0 [mm]. The bore dust should be put into a hermetically sealed container two minutes after drilling of the analyzed fragment of the borehole began. Such a container is equipped with steel spheres, which grind the coal during the eccentric motion. Subsequently, the gas from the container is analyzed with respect to its amount and composition, and the coal is subjected to a technical analysis. The amount of methane per mass unit of pure coal substance is calculated on the basis of the determined parameters. The loss of gas is determined arbitrarily, regardless of additional parameters, as the factor 1.12, by which the calculated value of the coalbed methane content is multiplied.

Part of the metrological procedure connected with collecting the coal sample is completed in the excavation, whereas grinding and the remaining measurements are performed in a laboratory. The measurement method is complex. There are a lot of parameters and factors that influence the end result. The most important ones are: the volume of coal substance, the capacity of the container with the sample, the volumes of the grinding spheres, the accuracy of outgassing of the sample, and the accuracy of balancing the amount and composition of the gas released from coal (indirectly, the degree of coal comminution). Such complex metrological measurements often generate measurement uncertainties. These were estimated in 2007 by means of comparative studies conducted by The Research and Supervisory Centre of Underground Mining (Ryszka and Sporysz 2008), on the initiative of the Chairman of The State Mining Authority. Comparative studies regarding the process of determining coalbed methane content by authorized units were carried out in two stages. Four units took part in the first stage. The results of the process of determining methane-bearing capacity, according to the methodology based on the direct method – the borehole method (Tarnowski 1992; GIG, paper No. 530002101/36 1976), for theoretically identical samples, were as follows: 3.88 m^3/Mg_{daf}, 4.81 m^3/Mg_{daf}, 6.26 m^3/Mg_{daf}, 5.48 m^3/Mg_{daf}. In the second stage, seven units participated. The obtained results were: 3.14 m^3/Mg_{daf}, 3.84 m^3/Mg_{daf}, 4.44 m^3/Mg_{daf}, 4.42 m^3/Mg_{daf}, 3.53 m^3/Mg_{daf}, 5.13 m^3/Mg_{daf}, 2.73 m^3/Mg_{daf}. In extreme cases, the relative differences between the obtained result and the mean value for particular series exceeded 23% and 31%, respectively. A given coal seam may be classified as belonging to the 2nd, 3rd, or 4th category of methane hazards as a result of such errors. These studies show how difficult the process of measuring the coalbed methane content is, due to its multi-complex nature.

The Polish PN-G-44200:2013-10 standard makes it possible to use the desorption intensity index *dp* to determine the approximate coalbed methane content (the document stresses the relationship between *MC* and *dp* as a linear function. The desorption intensity index is determined between the 2nd and 4th minute after the start of the drilling of the proper fragment of the borehole. Before the bore dust leaving the borehole is placed in the container of the desorbometer, it is sieved, so that a 0.5–1.0 [mm] grain fraction is extracted. The amount of the bore dust is determined using volume. The desorbometer – a U-tube – measures the pressure generated by the gas released from the sample (Stączek and Simka 2004). The measurement carried out in underground conditions is fast, easy, and yields an almost immediate result. In many countries, separate desorbometric methods were developed (Wierzbicki and Skoczylas 2014). It is often the case that the desorbable methane content *DMC* in coal – which is the amount of methane released to the excavation atmosphere under the local pressure – is regarded as the only parameter determining the value of *dp*. However, from the point of view of analyzing the physics of methane release from coal grains, the measurement performed by the desorbometer makes it possible to register just a very short period within a much longer process, and, what is also important, the registered value depends both on *DMC* and *De*. Certainly, fast desorbometric methods, which exclude *De*, do not generate results that are proportional to the content of methane in coal. However, if we assume the occurrence of slight local changes of *De*, one can discern some correlation between the values of *MC* and *dp*, in a limited area of mining activity. However, it needs to be remembered that the changeability of *De* is so considerable – be it as a result of different seams, different seam parts, of geological distortions – that neglecting the impact of this factor upon the result of the *dp* measurement makes it more difficult to use this parameter as a determinant of methane content in coal.

In order to show the scale of the impact of the kinetics of methane release – described by means of the effective diffusion coefficient *De* – upon the measurement of the desorption intensity index *dp*, two curves were generated (on the basis of Crank's diffusion model), presenting the temporal courses of methane release from coal grains. The red curve describes the release of methane from coal whose *DMC* = 8 cm^3CH_4/g and *De* = $0.2 \cdot 10^{-9}$ cm^2/s, for the 0.5–1.0 [mm] grain fraction, used to determine the desorption intensity index. In the case of the blue curve, the grain fraction remains the same, but *DMC* = 4 cm^3CH_4/g and *De* = $5 \cdot 10^{-9}$ cm^2/s. Figure 1 presents the kinetics of methane release within the duration of a week; Figure 2 – within the duration of 5 minutes, with the essential fragment corresponding to the *dp* measurement between the 2nd and the 4th minute. During that time, the value of methane release from coal of *DMC* = 8 cm^3CH_4/g was 0.05 cm^3CH_4/g. In the case of coal of *DMC* = 4 cm^3CH_4/g, the value of methane release was over two times higher, i.e. 0.12 cm^3CH_4/g. The value of *dp* would be much higher for coal characterized by *DMC* twice

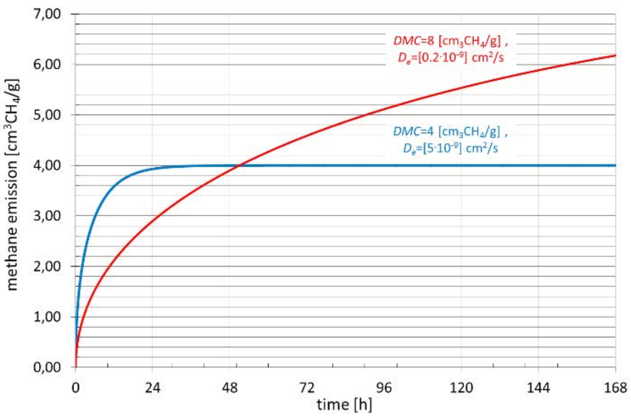


Fig. 1. The kinetics of methane release compatible with Crank's model, differing with respect to the *DMC* and *De* values – a week's time perspective

Rys. 1. Kinetyki emisji metanu zgodne z modelem Cranka różniące się wartościami desorbowalnej zawartości metanu oraz efektywnego współczynnika dyfuzji – tygodniowa perspektywa czasow

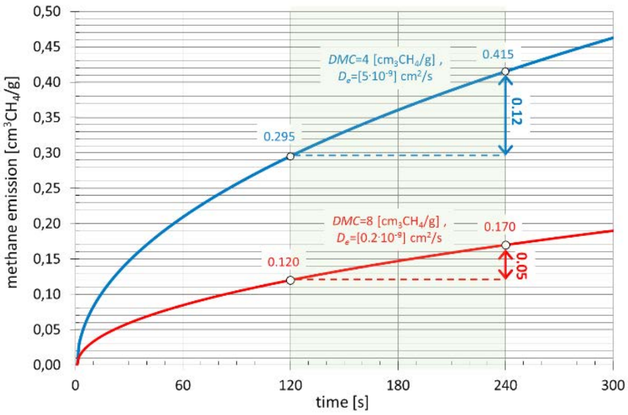


Fig. 2. The kinetics of methane release compatible with Crank's model, differing with respect to the *DMC* and *De* values – a 5-minute time perspective

Rys. 2. Kinetyki emisji metanu zgodne z modelem Cranka różniące się wartościami desorbowalnej zawartości metanu oraz efektywnego współczynnika dyfuzji – pięcio-minutowa perspektywa czasowa

lower, and it needs to be stated that this phenomenon can be explained only by different values of *De*.

In order to ensure full uniqueness of desorbometric measurements, one should register the process of methane release until the values close to the asymptotic ones are reached. For the grain fraction used in the desorbometer, this becomes difficult, as such a measurement would last from several days to several weeks, depending on the value of the effective diffusion coefficient. The solution proposed by the author involves a considerable reduction of the grain fraction, so that – after 24 hours – it would be possible to know the value of *DMC* and *De*. The method combines the advantages of the desorbometric measurement – a simple measurement taken in underground conditions, based on the essential laws of physics – with the measurement of the coalbed methane content, since the direct result is the desorbable methane content in coal, which successfully illustrates methane-bearing capacity and the effective diffusion coefficient.

In order to determine the optimal grain fraction, courses of methane release were generated (Fig. 3 and 4) on the basis of Crank's model, for coal whose *DMC* = 10 $\mathrm{cm^3CH_4/g}$ and *De* = 1.28 $\mathrm{cm^2/s}$. The value of the analyzed *De* is the mean of the determined values for various coal seams in the "Borynia-Zofiówka-Jastrzębie" hard coal mine, Ruch Zofiówka, obtained in the course of 16 measurements performed in 30°C (Table 1).

For the analyzed value of *De,* methane release approximates the asymptotic value after ca. 5 days for the 0.50–1.00 [mm] grain fraction; after ca. 2 days for the 0.315–0.50 [mm], grain fraction; and after 24 hours and 12 hours for the 0.250–0.315 [mm] and 0.20–0.25 [mm] grain fractions, respectively. Due to the occurrence of coals in which the *De* values exceed the analyzed mean value, the reasonable choice is the lowest of the aforementioned fractions.

Table 1. The values of *De* determined for various coal seams in the "Borynia-Zofiówka-Jastrzębie" hard coal mine in 30°C

Tabela 1. Wartości *De* określone dla różnych pokładów w KWK Borynia-Zofiówka-Jastrzębie w temperaturze 30°C

Effective diffusion coefficient D_e ($\times10^{-9}$) [cm^2/s]																$\overline{D_e}$
1.70	1.81	1.48	9.11	0.99	0.71	1.87	1.67	1.41	1.92	1.55	0.69	1.10	0.68	1.76	0.16	1,28E-09

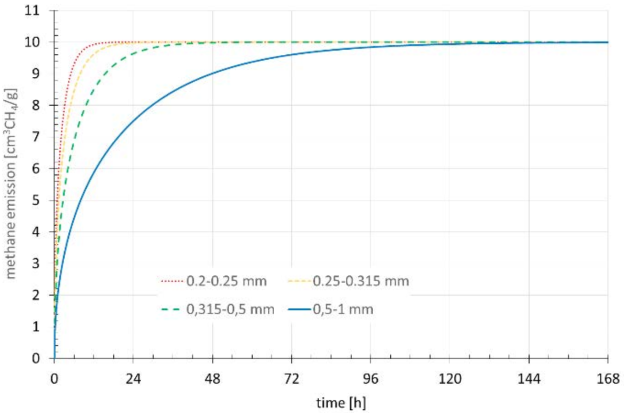


Fig. 3. The kinetics of methane release compatible with Crank's model for various grain fractions – a week's time perspective

Rys. 3. Kinetyki emisji metanu zgodne z modelem Cranka dla różnych klas ziarnowych – tygodniowa perspektywa czasowa

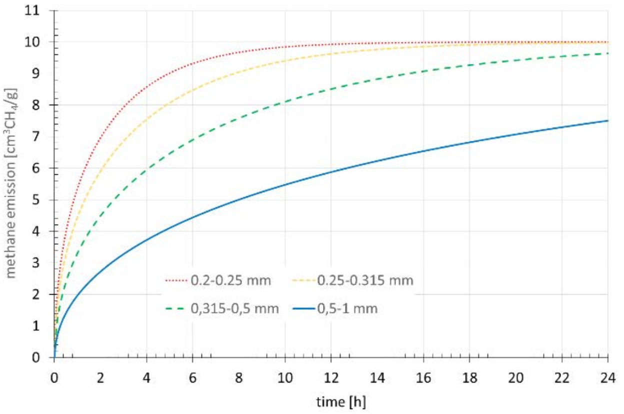


Fig. 4. The kinetics of methane release compatible with Crank's model for various grain fractions – a 24-hour time perspective

Rys. 4. Kinetyki emisji metanu zgodne z modelem Cranka dla różnych klas ziarnowych – dobowa perspektywa czasowa

For the 0.50–1.00 [mm] grain fraction, used to determine the desorption intensity index, the substitute radius is 0.35 mm, and for the 0.20–0.25 [mm] grain fraction – 0.11 mm. On the basis of formula (2) – one should raise the quotient of substitute radii to the power of two, which translates into an increase in the pace of methane release of 9.7 times in order to establish the change in the speed of methane release occurring with the change of the grain fraction. Such a radical change required developing new tools and measurement methods, which are described below.

3. The structure and physical foundations of a measurement performed with the Digital Methane Emission Recorder (DMER)

The concept of changing the measurement method proved feasible due to developing an innovative metrological instrument (UP RP: P398973) called the Digital Methane Emission Recorder (DMER). The instrument (cf. Figure 5) has two chambers – the measuring (2) and

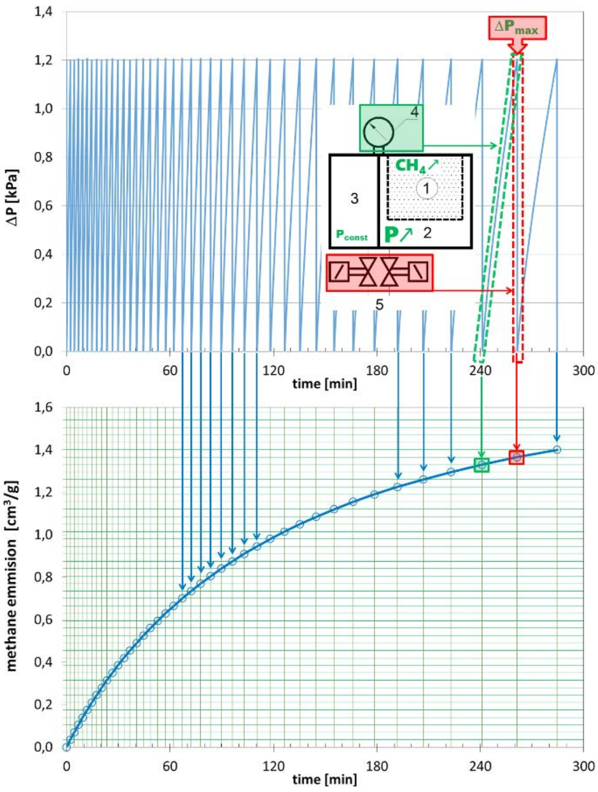


Fig. 5. DMER – a schematic depiction of the structure and functioning of the device

Rys. 5. Schemat budowy i zasada pomiaru Cyfrowym Rejestratorem Emisji Metanu the reference one (3). The differential pressure between the chambers is registered by the precise pressure transducer (4). The chambers are connected to the external environment by means of micro-electrovalves (5). Into the measuring chamber, the container with a coal sample is twisted (1). Methane desorbing from coal causes an increase in the pressure in the measuring chamber in relation to the reference chamber. The pressure transducer (4) registers an increase in the pressure in the measuring chamber. When the pressure value approximates the upper limit of the measuring range of the pressure transducer, the micro-electrovalves (5) open for ca. 0.1s. This levels the differential pressure in the measuring chamber in relation to the reference chamber. Each measurement cycle (opening the mini-electrovalves, levelling the pressures, closing the mini-electrovalves, an increase in the pressure in the measuring chamber due to methane release, reaching the limit of the transducer's measuring range, opening the mini-electrovalves again) constitutes the registration of a "quantum" of the volume of the methane released. Cyclical functioning of the device within a two-chamber system equipped with a differential transducer ensures quasi-isobaric conditions, makes it possible to introduce a transducer of high sensitivity, and reduces the impact of temperature changes on pressure changes. A typical number of measurement cy-

Fig. 6. DMER – photographs

Rys. 6. Cyfrowy Rejestrator Emisji Metanu – zdjęcia cles exceeds 100 – thus, it becomes possible to delineate the course of methane release in an accurate way, analyzing only the time when the micro-electrovalves are open. A series of test copies of the instrument was built on the basis of the discussed concept (cf. Figure 6), which was subsequently used in underground research.

4. Measuring the desorbable methane content – the methodology of underground measurements

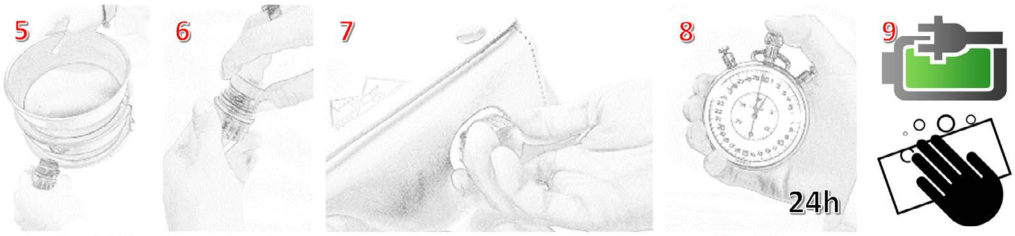
The methodology of measuring the desorbable methane content in coal and the effective diffusion coefficient with the Digital Methane Emission Recorder was simplified as much as possible, so that the difficult requirements of the underground environment could be met. The measurement itself is much more direct than in the case of the bore dust method of estimating the coalbed methane content. Inside the excavation, the instrument should be first prepared (Fig. 7), and then started (1, 2). When the drilling of the section of the research borehole begins, we initiate the measurement procedure by pressing the ↑ button (3). Then, we collect and sieve the bore dust (4). The sieved bore dust is placed inside the sample container (5, 6). The container is twisted into the instrument (7). The microprocessor system registers a change in the differential pressure which signals the beginning of the methane release. The system performs cyclical measurements of changes in the differential pressure for approx. 24 hours (8), until the state of sorption equilibrium is reached.

Prepare DMER device and sieves

Turn on the DMER by pressing central button

Together with the start of coal drilling run the measurement by pressing left button

Get drill cuttings and put tchem on the sieves



The sieved drill cuttings put into the container to completely fill its volume

Screw the container into the DMER

After 24 hours, read the result

Charge the battery, clean the device

Fig. 7. The methodology of measurements performed with DMER

Rys. 7. Metodyka pomiarowa Cyfrowym Rejestratorem Emisji Metanu

The 0.2–0.25 [mm] grain fraction is well represented in the bore dust collected from research boreholes. Initiating the measurement in underground conditions is easy and fast (Fig. 8). The instrument itself is small, with a keyboard simplified to the maximum and a clear display.

Fig. 8. A measurement in underground conditions: preparing the instrument, collecting the bore dust, placing the sample inside the instrument, the instrument at work

Rys. 8. Pomiar w warunkach kopalnianych: przygotowanie urządzenia, pobór zwiercin, umieszczenie próbki w urządzeniu, praca urządzenia

The instrument automatically calculates the loss of gas and takes it into account. On the basis of Crank's model, on the basis of the course extrapolation, it yields the projected *DMC* and *De* values, as well as the estimated *MC* value as early as after one hour.

5. The results of underground measurements

The measurements were performed in the following hard coal mines: "Pniówek", "Borynia-Zofiówka-Jastrzębie" Ruch Zofiówka, "Budryk", and "Brzeszcze". All in, seventeen measurements of the desorbable methane content were made with the DMER instrument. Each measurement was accompanied by determining the coalbed methane content by means of the bore dust method, according to the PN G-44200:2013 standard, as well as analyzing the desorption intensity index and the technical parameters of coal. An example of the direct result of such a measurement is presented in Figure 9. The dotted line marks the theoretical curve of Crank's model fitted into the chart.

A characteristic feature of direct results is lack of measurement points in the first several minutes of the process. This is the time between the start of the drilling of the investigated borehole section and placing the sample in the measuring instrument, often referred to as a gas loss. In the discussed methodology, this time is not arbitrarily determined, as – in underground conditions – the process of collecting and sieving bore dust may last shorter or longer each time. The amount of the lost methane can be amended with the radical relationship (3), which accurately describes the methane release at its initial stage (Figure 10).

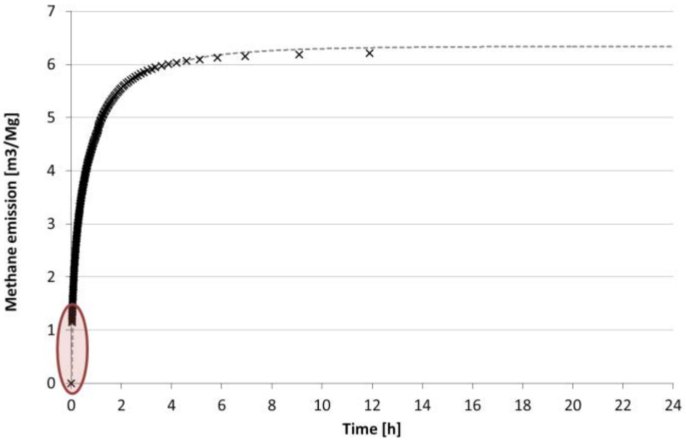


Fig. 9. The direct measurement results with the marked area of "gas loss"

Rys. 9. Bezpośrednie wyniku pomiaru – zaznaczony obszar „strat gazu"

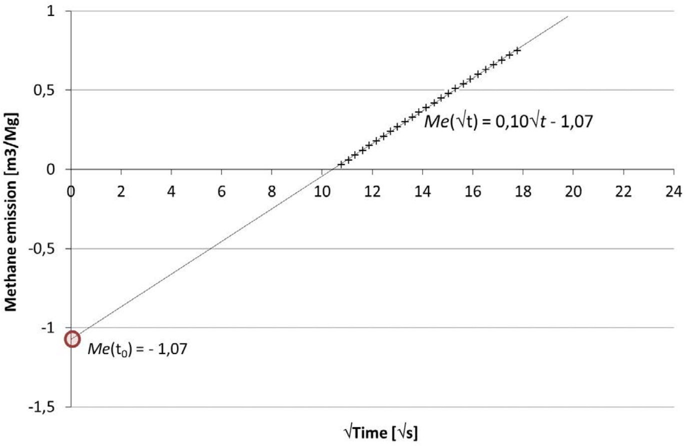


Fig. 10. The direct measurement results – amending "gas losses" with equation (3)

Rys. 10. Bezpośrednie wyniku pomiaru – korekta „strat gazu" równaniem (3)

The procedure of amending gas losses is performed automatically, by means of the microprocessor system of the analyzer. An essential advantage of the described method is the fact that it calculated gas losses individually for each sample, as different dynamics of methane release makes it difficult to determine the value of some universal amendment.

After amending gas losses, the asymptotic value of the registered release is the desorbable methane content *DMC* in coal. This parameter, from the perspective of evaluating the methane hazard and gas and rock outburst hazard, is very important, as it informs us about the maximum amount of methane that can be released into the excavation during the exploitation process. Since the mining industry in the majority of countries actively exploiting coal seams treats the coalbed methane content *MC* as the basic parameter determining the content of methane in coal (Wierzbicki and Skoczylas 2014), the *DMC* value should be completed with the free gas *FG* and the sorption capacity *SC* understood as the content of gas under the pressure of 1 bar (Kudasik 2016). The content of free gas is determined by the porosity of coal and the value of the seam pressure. Typically, the porosity of coals from the Upper Silesian Coal Basin falls within the range of 5–10% (Orzechowska-Zięba and Nodzeński 2008), which, for typical values of the seam pressure – 0.2–0.6 [MPa] (Skoczylas 2012) – gives us the amount of methane (Dutka et al 2009) within the range of 0.067––0.400 [m^3/Mgcsw] (the upper limit concerns coal of the highest porosity, for the highest value of the seam pressure). The value of sorption capacity *SC* for the pressure a_{1bar} determined in the laboratory conditions for the temperature of 30°C falls within the range of ca. 1.7 m^3/Mgcsw – ca. 2.5m^3/Mgcsw.

Table 2. The results of underground measurements

Tabela 2. Wyniki pomiarów kopalnianych

No.	Dp	Desorbable Methane Content *DMER*	Predicted methane content *DMER*	Methane Content PN-G 44200:2013 *MC*	Absolute error $\lvert MC - DMER \rvert$	Percentage relative error $\frac{\lvert MC - DMER \rvert}{MC}100$
	kPa	m^{3}CH$_4$/Mg	m^{3}CH$_4$/Mg	m^{3}CH$_4$/Mg	m^{3}CH$_4$/Mg	%
1	1.16	4.44	6.69	6.50	0.19	2.9
2	1.62	4.32	6.57	6.43	0.14	2.2
3	1.50	5.72	7.97	7.60	0.37	4.8
4	1.44	4.35	6.60	6.55	0.05	0.7
5	1.14	4.87	7.12	7.55	0.43	5.7
6	0.88	4.71	6.96	7.25	0.29	4.0
7	0.98	4.03	6.28	6.48	0.20	3.1
8	1.46	5.21	7.46	7.86	0.40	5.1
9	1.18	3.35	5.60	5.70	0.10	1.8
10	1.54	5.46	7.71	8.98	1.27	14.1
11	1.30	4.74	6.99	8.58	1.59	18.5
12	1.74	7.40	9.65	8.95	0.70	7.8
13	1.72	5.58	7.83	8.25	0.42	5.1
14	1.88	4.18	6.43	6.57	0.14	2.1
15	1.56	6.55	8.80	7.32	1.48	20.2
16	1.70	4.78	7.03	7.21	0.18	2.5
17	1.40	3.35	5.60	5.12	0.48	9.4

Therefore, it can be assumed that $MC = DMC + FG + SC = DMC + 2.25$ (+/–0.4) [m^3/Mg]. This line of reasoning shows that measuring the desorbable methane content is of key importance when it comes to determining the value and, in particular, the changeability of the coalbed methane content in a coal seam.

The results of underground measurements were presented in Table 2. The *dp* column contains the values of the desorption intensity index determined during the measurements of the coalbed methane content. The Desorbable Methane Content (DMER) contains the direct result of the measurement performed according to the innovative method, with the instrument presented in this paper. The measurement takes the compensated gas loss into account. In the Predicted Methane Content DMER column, values from the previous column, enlarged by the averaged factor 2.25 m^3/Mg are included, representing the averaged content of the free gas *FG* and the sorption capacity *SC*. These values are juxtaposed with the Methane Content *MC* column, containing the results determined according to the norm PN-G 44200:2013. The remaining two columns contain the absolute error and the percentage relative error.

Figure 11 presents the results of measurements in the form of bar charts. The blue color corresponds with the values of the predicted methane content determined with the DMER instrument, and the red color corresponds with the values of the methane content *MC*. Percentage relative errors were presented in Figure 12. The percentage relative errors between the two methods exceed 10% only in the case of three measurements. The relative percentage error did not exceed 5% in the case of half of the measurements. The average percentage relative error was 6.5%. Additionally, it needs to be emphasized that treating the coalbed methane content measurements performed with the bore dust method as a model procedure is only arbitrary, as the complex measurement procedure, regardless of all the care, generates substantial measurement uncertainties. If we juxtapose the obtained results with the

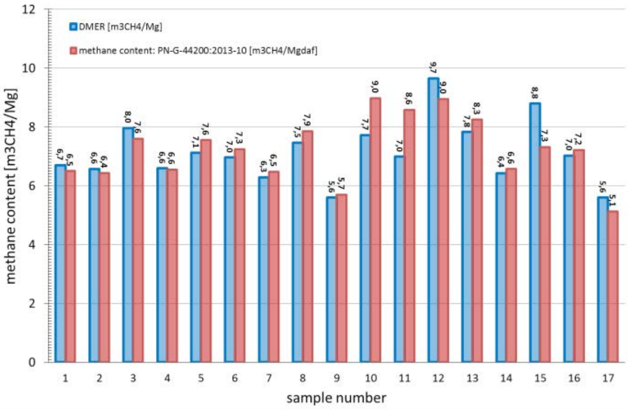


Fig. 11. Comparing measurement results: blue – predicted methane content determined with the DMER instrument; red – methane content *MC* determined according to the norm PN G-44200:2013

Rys. 11. Porównanie wyników pomiarów: kolor niebieski – przewidywana zawartość metanu określona cyfrowym rejestratorem emisji metanu, kolor czerwonym – metanonośność określona zgodnie z normą PN G-44200:2013

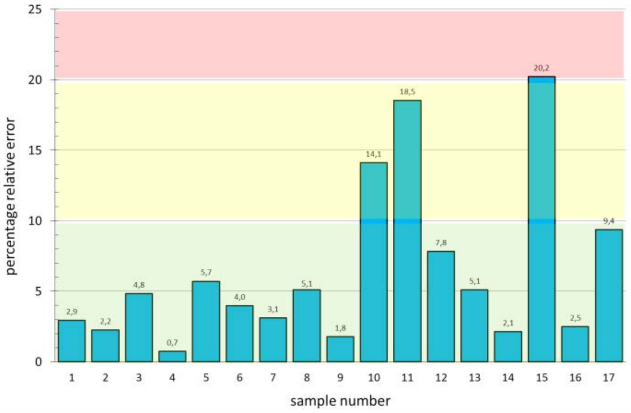


Fig. 12. Percentage relative error of the measurements: predicted methane content DMER in relation to methane content *MC*

Rys. 12. Procentowy błąd względny pomiarów wykonanych badanym urządzeniem względem metanonośności oznaczonej zgodnie z normą PN G-44200:2013

discrepancies in determining the coalbed methane content by authorized units, discussed in Chapter 3, we shall come to the conclusion that the discussed simplified method fulfills the expectations of the researchers.

Juxtaposing the direct results of the desorbable methane content with the measurements of the coalbed methane content required taking the correction representing the amount of the free gas *FG* and the sorption capacity *SC* into account. An attempt was made to optimize the value of the correction taking *FG* and *SC* into account. To this end, the sum of squared deviations *ssd* in the function of the *correction* value was calculated (Fig. 13) for the performed measurements *MC* and (*DMC* + *correction*). The minimum of the *ssd* functions corresponds

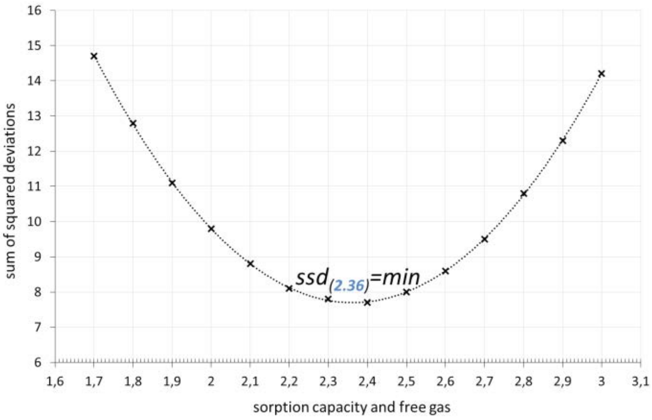


Fig. 13. Sum of squared deviations for the performed measurements of *MC* and (*DMC* + *correction*) in the *correction* function

Rys. 13. Suma kwadratów odchyłek dla wykonanych pomiarów metanonośności i desorbowalnej zawartości metanu uzupełnionej o poprawkę uwzględniającą pojemność sorpcyjną i gaz wolny w funkcji wartości poprawki with the *correction* value of 2.36 m^{3}CH$_4$/Mg. The value of the *correction*, when slightly enlarged, reduces the mean relative error from 6.5% to 6.3%.

The advantage of the analysis of the full process of methane release from coal in relation to the observation of its short fragment can be presented on the basis of the registered courses of methane release (Figure 14 – sample No. 16, Figure 15 – sample No. 6). The analyses

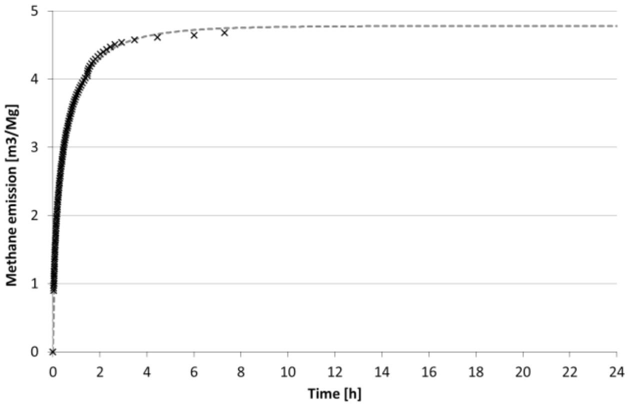


Fig. 14. Release of methane from sample No. 16 registered with the DMER instrument, *DMC* = 4.78 m^{3}CH$_4$/Mg, *correction* 2.25 m^{3}CH$_4$/Mg, *Predicted methane content DMER* 7.03 m^{3}CH$_4$/Mg, *Mn* = 7.21 m^{3}CH$_4$/Mg$_{daf}$, *dp* = 1.70 kPa *De* = 4.6 · 10^{-9} cm^2/s, V_{daf} = 26,26 %

Rys. 14. Emisja metanu z próbki nr 16 zarejestrowana cyfrowym rejestratorem emisji metanu, desorbowalna zawartość metanu = 4,78 m^{3}CH$_4$/Mg, poprawka = 2,25 m^{3}CH$_4$/Mg, oszacowana metanonośność = 7,03 m^{3}CH$_4$/Mg, metanonośność zgodnie z normą *Mn* = 7,21 m^{3}CH$_4$/Mg$_{daf}$, *dp* = 1.70 kPa, *De* = 4,6 · 10^{-9}, V_{daf} = 26,26%

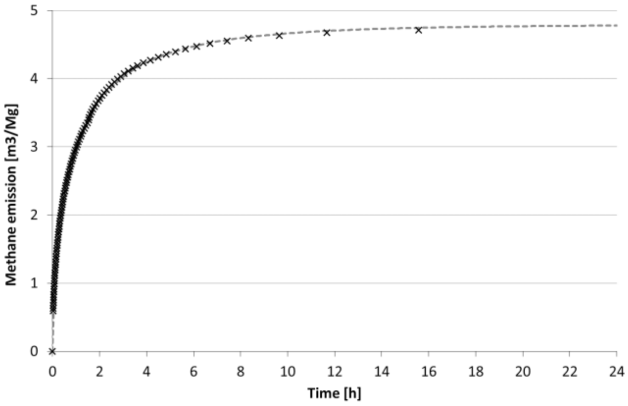


Fig. 15. Release of methane from sample No. 6 registered with the DMER instrument, *DMC* = 4.71 m^{3}CH$_4$/Mg, *correction* 2.25 m^{3}CH$_4$/Mg, *Predicted methane content DMER* 6.96 m^{3}CH$_4$/Mg, *Mn* = 7.25 m^{3}CH$_4$/Mg$_{daf}$, *dp* = 0.88 kPa *De* = 2.1 · 10^{-9} cm^2/s, V_{daf} = 29,50 %

Rys. 15. Emisja metanu z próbki nr 6 zarejestrowana cyfrowym rejestratorem emisji metanu, desorbowalna zawartość metanu = 4,71 m^{3}CH$_4$/Mg, poprawka 2,5 m^{3}CH$_4$/Mg, oszacowana metanonośność = 6,96 m^{3}CH$_4$/Mg, metanonośność zgodnie z normą *Mn* = 7,25 m^{3}CH$_4$/Mg$_{daf}$, *dp* = 0,88 kPa, *De* = 2,1 · 10^{-9}, V_{daf} = 29,50%

were performed in different mines ("Pniówek" and "Budryk"), which resulted in substantial differences between the values of the effective diffusion coefficients. Coals No. 16 and No. 6, according to the measurements performed with the DMER device, were characterized by the effective diffusion coefficients of, respectively, $4.6 \cdot 10^{-9}$ cm^2/s and $2.1 \cdot 10^{-9}$ cm^2/s. The procedure of determining the coalbed methane content with the bore dust method for both samples yielded similar results – 7.21 m^3/Mg$_{daf}$ and 7.25 m^3/Mg$_{daf}$, respectively. The innovative method using the DMER instrument, with the correction regarding *FG* and *SC* taken into account, made it possible to estimate the coalbed methane content to be 7.03 m^3/Mg and 6.96 m^3/Mg, respectively. The differences between the analyzed methods were merely ca. 3%, which – considering the substitute differences in measurement methodologies – lets us suppose that the actual values of the coalbed methane content for both coals were similar. The values of the desorption intensity index differed considerably for the same samples (1.70 kPa and 0.88 kPa, respectively).

In order to explain the substantial differences in the values of the desorption intensity index (in spite of the compatibility of the values of the coalbed methane content), one should analyze the initial stages of the kinetics of methane release (Figures 16 and 17). Taking into account the value of the effective diffusion coefficient for sample No. 16 – over two times higher in relation to the value for sample No. 6) – with the compatibility of the asymptotic values (*DMC*), means that the same amounts of methane will be released from a sample characterized by a higher value of the effective diffusion coefficient within a period of time over two times shorter. Thus, we can state that during the short initial stage of methane release, registered during the measurement of the desorption intensity index, in spite of compatible coalbed methane content values, the amount of methane that is ca. twice as large shall be released from a sample characterized by the effective diffusion coefficient that is twice as high. This will give us the value of the desorption intensity index that shall be approx. two times higher.

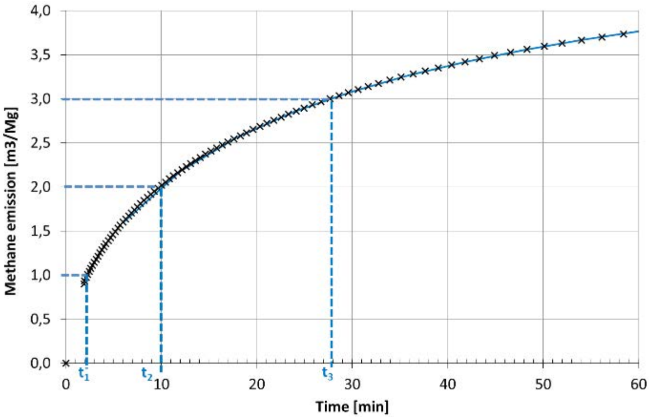


Fig. 16. The initial stage of methane release from sample No. 16, registered with the DMER instrument

Rys. 16. Początkowy fragment emisji metanu z próbki nr 16 zarejestrowany urządzeniem cyfrowym rejestratorem emisji metanu

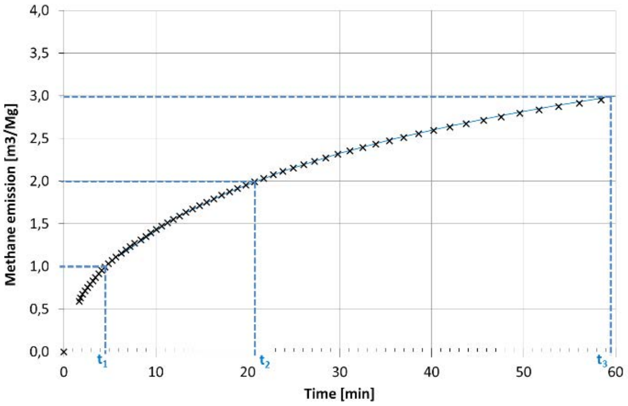


Fig. 17. The initial stage of methane release from sample No. 6, registered with the DMER instrument

Rys. 17. Początkowy fragment emisji metanu z próbki nr 6 zarejestrowany urządzeniem cyfrowym rejestratorem emisji metanu

Summary

Thorough and up-to-date information about the parameters of the coal-methane system, which influence the methane hazard and methane and rock outburst hazard, determines the right prevention measures – and is indispensable when it comes to exploiting coal seams. In order to ensure continuity of coal extraction and optimize spending on prevention, we need to apply an inexpensive and quick method of evaluating coalbed methane content, which makes it possible to formulate local predictions during conducting mining activities. Fast evaluation of the coalbed methane content of coal should contribute to improvement in exploitation conditions, enhance safety of mining activities, and result in increasing – or maintaining – production capacities of numerous hard coal mines.

The procedure of determining the coalbed methane content by means of the bore dust method, according to the PN G-44200:2013 standard, is complicated and multi-complex in its nature. It requires determining a lot of indirect parameters; the constant amendment of the gas loss is taken into account in an arbitrary way; the measurement itself is time-consuming, as it combines underground and laboratory research. The results of comparative studies into determining the coalbed methane content in replicable samples by authorized units point to discrepancies in relation to the mean value, reaching as much as 30%. It is the opinion of the author that following the methodology in a strict way, accuracy applied at each stage of the research, as well as using advanced metrological tools, should result in determining the reliable value of the coalbed methane content.

Classic desorbometric methods are fast, direct, and performed in underground conditions. They generate results on the basis of investigating a short fragment of the process of methane release from a granular coal sample. The desorption intensity index, measured between the 2nd and 4th minute, represents the process of methane release, the asymptotic value of which is reached after several, or about a dozen days. The value of the desorption intensity index is often identified with the coalbed methane content; however, both the desorbable methane content and the effective diffusion coefficient influence the result of the measurement in a significant way. The present paper describes the measurement of the coalbed methane content performed on two samples. The results – obtained both in the course of the bore dust method and the method developed by the author – were compatible, but the values of the desorption intensity index differed considerably. The reason for this was the value of the effective diffusion coefficient – over two times higher for the coal the desorption intensity index of which was higher. If we assume that the effective diffusion coefficient changes slightly within individual coal parcels or seams, and if we eliminate the potential impact of geological distortions on the local fluctuations of the coefficient value, we can presume that the value of the desorption intensity index shall be correlated with the coalbed methane content in a satisfactory way.

The author proposes a deep modification of the classic desorbometric method, so that it is possible to register the full course of methane release from coal within a time period shorter than 24 hours. This can be achieved by a substantial reduction of the investigated grain fraction, to 0.20–0.25 [mm]. The presented concept of the measurement performed in underground conditions is carried out with an innovative measuring instrument – the Digital Methane Emission Recorder DMER. The instrument measures basic physical quantities – cyclical increases in the differential pressure between the measuring chamber and the reference chamber, resulting from methane release from coal. The direct measurement results are: the desorbable content of methane in coal and the effective diffusion coefficient. Each of them constitutes a basic parameter of the coal-methane system, describing both the amount of methane that can be released in the atmosphere of the excavation, and the speed with which it is released. The method assumes, and the instrument takes into account, the correction of the gas losses, determined separately for each sample. Estimating the coalbed methane content requires completing the desorbable methane content in coal with the free gas and the sorption capacity under the pressure of 1 bar. The small changeability of these parameters makes it possible to take their averaged values into consideration. The analysis of the results of seventeen underground measurements, performed according to the developed methodology and with the innovative device, together with the analysis of the accompanying measurements of the methane-bearing capacity, desorption intensity and other parameters, points to a high compatibility of the results obtained due to the method developed by the author with the results obtained with the bore dust method. The relative differences did not exceed 5% for half of the measurements,; they exceeded 10% only in the case of three measurements. It needs to be stated that the described method equals fast measurements performed in underground conditions. Additionally, the analysis of the changeability of the effective diffusion coefficient in a series of local measurements can provide us with information about unidentified geological distortions which are often accompanied by structural changes of coal, resulting in a considerable increase of the value of the effective diffusion coefficient. The presented method makes it possible to determine the value of the effective diffusion coefficient in underground conditions, which – with the usage of alternative methods – is possible only in laboratory conditions, with specialist equipment applied. The method proposed by the author combines all the advantages of fast underground measurements, and is free from their drawbacks.

Acknowledgements

The research was carried out as part of the LIDER/31/103/L-3/11/NCBR/2012 Project, financed by the National Centre for Research and Development.

REFERENCES

Dutka et al. 2013 – Dutka, B., Kudasik, M., Pokryszka, Z., Skoczylas, N., Topolnicki, J., Wierzbicki, M. 2013. Balance of CO_2/CH_4 exchange sorption in a coal briquette. *Fuel Processing Technology* 106, pp. 95–101.

Gawor, M. and Skoczylas, N. 2014. Sorption Rate of Carbon Dioxide on Coal. *Transport in Porous Media* 101(2), pp. 269–279.

Praca nr 530002101/36. *Metoda bezpośrednia – otworowa określania zawartości metanu w pokładach węgla 1976.* GIG KD „Barbara”.

Kudasik, M. 2016. The manometric sorptomat – an innovative volumetric instrument for sorption measurements performed under isobaric conditions. *Measurement Science and Technology* 27(3).

Pillalamarry et al. 2011 – Pillalamarry, M., Harpalani, S. and Liu, S. 2011. Gas diffusion behaviour of coal and its impact on production from coalbed methane reservoirs. *International Journal of Coal Geology* 86, pp. 342–348.

PN G-44200:2013, Mining – Determining Of Methane Content In Coal Seams – Drilling Method.

Ryszka, M. and Sporysz, G. 2008. Weryfikacja bezpośredniej metody oznaczania metanonośności pokładów węgla kamiennego stosowanej w polskim górnictwie, część II – porównania międzylaboratoryjne oznaczenia metanonośności węgla. *Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie* 9.

Skoczylas, N. 2012. Coal Seam Methane Pressure as a Parameter Determining the Level of the Outburst Risk–Laboratory and in Situ Research. *Archives of Mining Sciences* 57(4), pp. 861–869.

Skoczylas, N. 2014. Estimating gas and rock outburst risk on the basis of knowledge and experience–the expert system based on fuzzy logic. Archives of Mining Sciences 59(1), pp. 41–52.

Skoczylas, N. 2015. Analyzing the parameters of the coal-gas system by means of a low-cost device based on a flow meter. *Adsorption Science & Technology* 9.

Stączek, A. and Simka, A. 2004. Graniczny wskaźnik intensywności desorpcji gazu z węgla jako podstawowy parametr zagrożenia wyrzutowego charakteryzujący stopień nasycenia gazem pokładów węgla. *Mechanizacja i Automatyzacja Górnictwa* 42(12).

Tarnowski, J. 1992. Stosowane w kraju metody oznaczeń gazonośności złożowej. *Przegląd Górniczy* 9.

UP RP: P398973 Sposób rejestracji przebiegu emisji gazu desorbującego i analizator emisji gazu desorbującego

Wierzbicki, M. 2013. Changes in the sorption/diffusion kinetics of a coal-methane system caused by different temperatures and pressures. *Gospodarka Surowcami Mineralnymi – Mineral Resources Management* 29(4).

Wierzbicki, M. and Skoczylas, N. 2014. Evaluation and management of the gas and rock outburst hazard in the light of international legal regulations. *Archives of Mining Sciences* 59(4).

SZYBKA OCENA METANOŚNOŚCI WĘGLA JAKO ELEMENT POPRAWY WARUNKÓW EKSPLOATACJI

Słowa kluczowe

emisja metanu z węgla, metanonośność, zagrożenie wyrzutami metanu i skał, zagrożenie metanowe

Streszczenie

Metan jako kopalina towarzysząca występuje w większości zagłębi węglowych na świecie. Wiedza o zawartości metanu w węglu jest podstawową informacją wykorzystywaną do bilansowania i opisywania złoża, prowadzenia bezpiecznej eksploatacji węgla w obliczu zagrożeń metanowych oraz wyrzutami metanu i skał, czy też rzadszych działań, jak próby szczelinowania pokładu i pozyskiwania metanu, bądź składowania CO_2 w pokładach pozabilansowych. Autor przedstawia głęboko zmodyfikowaną metodę desorbometryczną wykorzystaną do analizy układu węgiel–metan. Badaniu w warunkach kopalnianych podlega pełen proces uwalniania metanu z węgla, co pozwala na określenie strat gazu, desobowalnej zawartości metanu oraz efektywnego współczynnika dyfuzji. Możliwość przeprowadzenia tego typu badań w czasie poniżej 24 godzin daje obniżenie klasy ziarnowej analizowanych zwiercin. Obszerne badania kopalniane poprzedzone zostały analizą modelową dotyczącą jednoczesnego wpływu desorbowalnej zawartości metanu w węglu oraz efektywnego współczynnika dyfuzji na wartość wskaźnika intensywności desorpcji. Opisany został wpływ klasy ziarnowej na kinetykę emisji metanu z węgla oraz dokonany został wybór klasy ziarnowej 0,20–0,25 mm, której zastosowanie pozwoliło na rejestrację pełnej emisji metanu z węgla w zakładanym czasie. Przedstawiona została autorska metodyka pomiarów kopalnianych oraz opisano urządzenie zastosowane do ich wykonania. Badania kopalniane polegały na pomiarach desorbowalnej zawartości metanu zgodnie z przedstawioną metodyką autorską, prowadzonych równolegle z badaniami metanonośności metodą zwiercinową, intensywności desorpcji oraz parametrów technicznych węgla. Wyniki badań wskazują na dużą zbieżność pomiędzy desorbowalną zawartością metanu w węglu a metanonośnością mierzoną metodą zwiercinową zgodnie z polską normą. Średni błąd względny procentowy dla 17 pomiarów wyniósł 6,5%. Przedstawiony został przykład wykorzystania efektywnego współczynnika dyfuzji dla wytłumaczenia znacznych różnic wskaźnika intensywności desorpcji dla dwóch próbek o zbliżonej metanonośności.

FAST EVALUATION OF THE COALBED METHANE CONTENT OF COAL VIEWED AS AN ELEMENT LEADING TO IMPROVEMENT IN EXPLOITATION CONDITIONS

Keywords

methane emission, coalbed methane content, methane and rock outburst, methane hazard

Abstract

Methane, as a co-occurring compound, can be found in the majority of coal basins all over the world. The knowledge of methane content is a basic piece of information used in balancing and describing a given coal seam, in conducting safe exploitation – with methane hazards and methane and rock outburst hazards in mind – as well as in less common procedures, such as coal seam fracturing and methane extraction, or storing carbon dioxide in off-balance coal seams. The author of the present paper outlines a thoroughly modified desorbometric method used to analyze the coal-methane system. The research object, in underground conditions, is the full process of releasing methane from coal, which makes it possible to determine gas losses, the desorbable methane content, and the effective diffusion coefficient. This type of research can be conducted in less than 24 hours due to the reduction of the grain fraction of the analyzed bore dust. The thorough research in underground conditions was preceded by a model analysis of the simultaneous impact of the desorbable methane content in coal and the effective diffusion coefficient upon the value of the desorption indensity index. The influence of a grain fraction on the kinetics of methane release from coal was described, and the 0.20–0.25 [mm] grain fraction was selected. The choice of this particular fraction made it possible to register the full process of methane release from coal, in the assumed time. An original methodology of performing underground measurements was presented, together with an instrument used to perform these measurements. The underground research involved measuring the desorbable methane content according to the presented original methodology, which was done simultaneously with an analysis of the coalbed methane content carried out by means of the bore dust method, an analysis of desorption intensity, and an analysis of the technical parameters of coal. The results point to a substantial discrepancy between the desorbable methane content in coal and the coalbed methane content measured by the bore hole method in compliance with the Polish standard. The mean relative percentage error for 17 measurements was 6.5%. The author provided an example concerning using the effective diffusion coefficient in explaining substantial differences in the desorption intensity index for two samples characterized by the similar coalbed methane content.