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THE OUTBURST RISK AS A FUNCTION OF THE METHANE CAPACITY AND FIRMNESS OF A COAL SEAM

ZAGROŻENIE WYRZUTOWE W FUNKCJI METANONOŚNOŚCI I ZWIĘZŁOŚCI – WYNIKI KOPALNIANIE ORAZ BADANIA LABORATORYJNE

In most coal basins that are currently being exploited, gas and rock outbursts pose a considerable safety threat. The risk of their occurrence is frequently assessed by means of a parameter known as the methane capacity of coal. In a lot of countries, the evaluation of the mechanical properties of coal is conducted by means of another parameter: the firmness of coal. Due to the laboratory investigations and in situ observations carried out by the authors of this paper, it was possible to determine a function space in which the outburst risk can be described as a function of the methane capacity and firmness of a coal seam. This, in turn, made it possible to link the „gas factor" to the „mechanical factor", and thus provide a more comprehensive risk analysis.

Keywords: gas and rock outburst, methane, firmness, outburst risk

Wyrzuty gazów i skał stanowią duże zagrożenie w większości obecnie eksploatowanych zagłębi węglowych. Bardzo często wykorzystywanym parametrem oceny stanu zagrożenia wyrzutowego jest zawartość metanu w węglu. W wielu krajach do oceny mechanicznych parametrów węgla wykorzystuje się zwięzłość.

Autorzy przeprowadzili badania laboratoryjne polegające na prowokacjach wyrzutów w skali laboratoryjnej. Jako materiał badawczy wykorzystane zostały brykiety węglowe. W trakcie badań wstępnych ustalona została zależność pomiędzy porowatością brykietów, a ich zwięzłością *f* oraz pomiędzy ciśnieniem nasycania metanem, a wskaźnikiem intensywności desorpcji *dP*. Pozwoliło to na przygotowywanie eksperymentów o kontrolowanych parametrach gazowych (wskaźnik intensywności desorpcji) oraz wytrzymałościowych (zwięzłość). Opracowana została metoda kontrolowania intensywności prowokacji wyrzutu poprzez określenie tempa spadku ciśnienia gazu przed czołem brykietu. Dzięki temu dla siatki parametrów *f-dP* możliwe było poszukiwanie minimalnej, skutecznej intensywności prowokacji wyrzutu. Znormalizowana wartość stałej czasowej spadku ciśnienia przed czołem brykietu powodującej skuteczną inicjację wyrzutu uznana została za miarę zagrożenia wyrzutowego dla rozpatrywanych parametrów *f-dP*. Dysponując wartościami tak określonych miar zagrożenia wyrzutowego dla całej siatki parametrów *f-dP* można wykreślić przestrzeń zagrożenia wyrzutowego w funkcji rozpatrywanych parametrów.

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Równoległa faza badań dotyczyła poszukiwania korelacji pomiędzy wskaźnikiem intensywności desorpcji, a zawartością gazu w węglu (metanonośnością *Mn*) na przykładzie pomiarów wykonanych w pokładzie 412 KWK „Zofiówka". W pokładzie tym zaobserwowano bardzo wyraźną, liniową zależność pomiędzy wskaźnikiem intensywności desorpcji, a metanonośnością. Poznanie funkcyjnej zależności *Mn*(*dP*) umożliwiło przedstawienie wyników prac laboratoryjnych jako przestrzeni zagrożenia wyrzutowego w funkcji zwięzłości i metanonośności.

Analiza uzyskanej przestrzeni zagrożenia wskazuje na jej zgodność zarówno z intuicją, jak i z kopalnianym doświadczeniem. Dla progowej w polskim górnictwie węglowym wartości zwięzłość ($f = 0.3$) stan zagrożenia wyrzutowego na poziomie 50% występuje przy *Mn* około 7 $m^3CH_4/Mg_{coal}{}^{daf}$. Aby zagwarantować podobny stan zagrożenia wyrzutowego dla kryterialnej wartości metanonośności na poziomie 8 [$m^3CH_4/Mg_{coal}{}^{daf}$] węgiel powinien mieć zwięzłość *f* powyżej 0.5. Oczywiście wartość izolinii na poziomie 50% jest umowna, a interpretacji powinny podlegać raczej kształty izolinii, niż ich wartości.

Słowa kluczowe: wyrzuty gazów i skał, metanonośność, zwięzłość, ryzyko wyrzutowe

1. Introduction

The risk of gas and rock outbursts is one of the principal factors responsible for the potential dangers to mining personnel. For over 150 years, scientists have investigated the nature of this phenomenon and perfected methods of risk analysis, carrying out various research and observations. In coal producing countries, numerous legal regulations aiming at improving the safety of miners working underground were implemented (Skoczylas & Wierzbicki, 2012). These regulations are based on investigations of a number of parameters, carried out both in mines and under laboratory conditions (Skoczylas et al., 2010). In most countries (including Poland), the basic parameter employed in the evaluation of the risk of gas and rock outbursts is the methane content in coal.

The authors of the present paper conducted laboratory research – based, in part, on observations carried out in mines – in order to determine the distribution of the outburst risk as a function of the methane capacity and firmness of coal. In Poland, the firmness of coal is regarded as the key parameter describing the strength properties of a given raw material. It is also frequently used for research purposes in other countries , e.g. China, Russia, and Ukraine.

2. The basic parameters used in the process of evaluating the risk of methane and rock outbursts in the Polish mining industry

2.1. The methane content in coal

The methane capacity of a coal seam is usually defined as the volumetric amount of CH_4 of natural origin per unit weight within the coal solid. It is one of the most important parameters determining the probability of occurrence of the outburst risk, and it is treated as such in mining facilities all over the world. Often, the methane capacity of a coal seam constitutes a basis for the outburst risk categorization. The criteria values, for selected countries, oscillate around 9 m^3/Mg_{csw} (± 1 m^3/Mg_{csw}) (Beamish & Crosdale, 1998; Lama & Bodziony, 1996): China – 10 m3/ Mg_{csw}; Australia, Bulgaria, and the Czech Republic – 9 m^3/Mg_{csw}; Ukraine, Hungary, and Poland – 8 m^3/Mg_{csw}. The works by Brandt (1987) and Lama (1995) indicate that the outbursts occur in coals whose methane capacity exceeds 8 m^3/Mg_{csw}. As far as the German regulations are concerned, the threshold limit value for the methane content in coal was established as 9 m^3/Mg_{csw} – in this case, it is the so-called desorbable content of methane in coal (the difference between the total methane content and the methane content under the pressure of 1 bar).

The methane capacity is most frequently determined by means of an analysis of a grain sample collected from a prospect hole. The sample is placed within a hermetic container and then comminuted. Subsequently, the amount of gas released from the sample is assessed, with free gas and gas loss modifications allowed for (the gass loss being the amount of gas released between the crushing of coal during the drillings and placing it in the hermetic container) (Wierzbicki, 2011). In Australia, the content of gas in a coal seam, as well as its composition, are analyzed by means of the AS 3980 method (core sample) or an equivalent, officially approved method. The relevant threshold limit values are not determined by any legislative body – this is the responsibility of particular mining facilities that are in charge of developing systems of outburst risk management.

Russian regulations concerning the coal seam exploitation under conditions of gas and rock outburst risk relate the threshold limit value of the gas content in coal to the V_{daf} paramater and the depth of the coal seam occurrence. For a change, the Chinese regulations do not treat gas content in coal as such a significant outburst parameter.

2.2. The firmness of coal

In a lot of countries, the major parameter describing the mechanical properties of coal is firmness – f (Protodyakonov impact strength index). The methodology by means of which the commpactness is determined is based on the statement that the energy consumed during the comminution of a rock is proportional to the newly generated surface area and the volume of the comminuted solid (Rittinger's law and Kick's law) (Lindqvist, 2008). The rules and the original version of the method for firmness determination were proposed in 1951 by Protodyakonov. The impact strength test, developed by this researcher, was subsequently used by Evans and Pomeroy (1966) to classify the coal seams in the UK. The procedure of determining the value of f is as follows: first, a coal sample is collected from a spot characterized by potentially the lowest firmness value. After that, the sample is comminuted into 10-20 mm grains. Aliquots of 50 g are placed in appropriately selected cylindrical containers, and crushed with a rammer of a given weight, dropped from a particular altitude for a proper number of times. Thus prepared, the comminuted coal material is sifted, and then the volume of the 0.5-1.0 mm grain fraction is determined. On its basis, the firmness index in the Protodyakonov's scale is established. Such a method of determining this index (or an analogous one) has been adopted by the mining industries of Poland, Russia, Ukraine, and China. In Poland, the threshold limit value as specified by the mining regulations is 0.3, whereas in China, it is 0.5. The Russian and Ukrainian regulations specify the threshold limit value for a combined parameter that comprises both firmness and the coal seam methane pressure.

2.3. The desorption intensity index

In numerous countries, mining regulations mention parameters defined on the basis of the analysis of the kinetics of methane release from a granular coal sample. These parameters are commonly referred to as desorption intensity. Desorption intensity is influenced by a number of factors, out of which the most important ones are the seam pressure of gas in a coal seam, the index of gas diffusion in coal, and the sorption isotherm.

In Poland, the *dP* desorption intensity index is used. It is measured on coal samples whose mass is ca. 3g. The measurement is performed by means of a manometric desorbometer, between the 120^{th} and the 240^{th} second after the start of the process of drilling a given section of a prospect hole (Strączek & Simka, 2004). Before the cuttings coming out of the hole are placed in the desorbometer's container, they are sifted, so that a required grain fraction is obtained (0.5-1 mm). The result of the measurement is expressed in kPa. The discussed parameter has its equivalents in various countries. In the Czech Republic, it is the V_1 parameter, denoting the intensity of desorption from a 10-gram sample representing the 0.5-0.8 mm grain fraction, measured in 35 s. In Germany, the $q_{0\text{-}1}$ parameter was introduced, expressed in m^3 per ton of coal (the measurement procedure lasts one minute). In Australia, the common practice is to determine Hargraves' emission velocity (gas release from a 4-gram coal sample; grain fraction 0.125-0.5 mm; measurement between the 2^{nd} and the 6^{th} minute). In China, the *DP* index is used, which denotes the initial rate of gas desorption from coal (a parameter similar to the *dP* index used in Poland).

Diversity of metrological devices and measuring techniques excludes direct comparison of the threshold limit values of the investigated parameters. For example, in Poland, the maximum safe value of the dP index, measured by means of a manometric desorbometer (Lama & Bodziony, 1998), was set as 1.2 kPa. In the Czech Republic – as in the case of the seam pressure – two threshold limit values were established: the values in the range of 1.0-1.5 cm^3 correspond to the first risk level, whereas any value exceeding 1.5 cm^3 indicates the second risk level. According to the German regulations, the dangerous value is $q_{0\text{-}1} > 2.3$ m^3/Mg.

3. The correlation between the desorption intensity index and the gas content in coal, as illustrated by the example of the measurements performed in the coal seam no. 412łg in the „Borynia-Zofiówka-Jastrzębie" hard coal mine

As it was stated in section 2.3, the value of the *dP* desorption intensity index is the amount of methane released from a sample of a particular size, within a particular time period. Thus, the value of the *dP* index will depend – among other things – on the kinetic properties of coal in relation to methane (these can be described by means of the D_e effective diffusion coefficient (Crank, 1975; Wierzbicki, 2011, 2013a, 2013b)), as well as on the initial content of methane in the sample, which, in the case of in situ research, is the methane capacity of the coal seam. In these mining facilities where the undergound mining works are carried out in hazardous areas, the values of methane and rock outburst risk indices (the *dP* index included) are measured every day. Additionally, the measurements of the methane capacity of these seams are performed each time the excavation has progressed another 50 m. The results of these measurements are subsequently presented in the form of statistics. Figure 1 shows the correlation between the value of the intensity index of a 2-minute desorption process and the methane capacity of the coal seam, obtained for the seam no. 412łg in the „Borynia-Zofiówka-Jastrzębie" hard coal mine, belonging to the Ruch Zofiówka company. For 107 pairs of the *dP-Mn* values, within the ranges $dP > 0.2$ and $Mn > 2$, the correlation between the desorption intensity index and the methane capacity can be described by means of the following formula: $Mn = 3.20dp + 1.62$ [m^3/Mg].

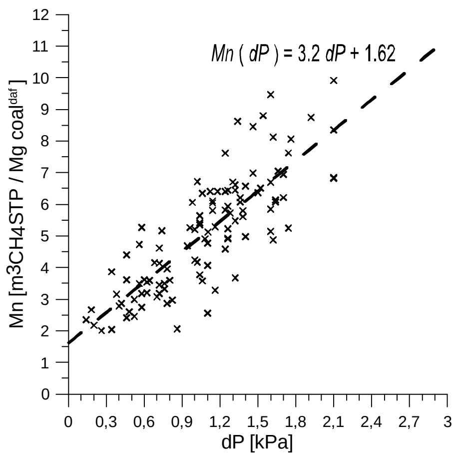

Fig. 1. A sample correlation between the desorption intensity index and the methane capacity of coal, obtained for the seam no. 412łg in the „Borynia-Zofiówka-Jastrzębie" Ruch Zofiówka hard coal mine

The existence of the linear correlation between the desorption intensity index and the methane capacity is testified, among other sources, by the research discussed in the works by (Borowski, 1976; Szlązak, 2011).

4. Provoking outbursts in the laboratory environment, under the conditions of the controlled provocation intensity

The authors of the present paper carried out laboratory research which involved provoking a series of micro-outbursts, for different firmness and methane content values. Since analogous research (concerning some other gas parameters) was thoroughly discussed in the works by (Skoczylas, 2012a, b), only a concise description of the investigations in question will be provided below, with particular emphasis placed on the differences that occurred.

The research material was a coal briquette, properly prepared. Such a choice was dictated by the fact that it is possible to prepare congruent briquettes, characterized by controlled parameters. At the Strata Mechanics Research Institute, briquettes have often been used in resarch into outbursts, each time proving their usefulness in such investigations (Skoczylas, 2009). The briquette in question was formed in an „outburst pipe", where experiments were also conducted. Before each measurement, for 24 hours, the briquette was subjected to outgassing so that vacuum would be created, and saturated with methane until the pressure value appropriate for the investigated conditions was reached.

The research was conducted in such a way as to ensure the control over the intensity of the outburst provocation. Thus, the main objective was to find the minimal intensity for the outburst provocation (outburst susceptibility), guaranteeing a successful outburst (Fig. 2).

The outburst susceptibility, defined in this way, can be treated as a certain criterion for determining the outburst risk for particular mining conditions – in this particular case, described by means of the two parameters: *f*, *Mn*. From the perspective of the experiment, this provocation

Fig. 2. Briquette destroyed as a result of an outburst induced under laboratory conditions

intensity was, in fact, the minimum value of the time constant of the rate of the pressure drop ahead of the briquette front. When a successful initiation of an outburst required generating a fast pressure drop ahead of the briquette front (in this case, the arising gas stress values were high), the level of outburst risk under the given conditions *f*, *Mn* was low. The opposite occurred when, for the investigated conditions *f*, *Mn* even a slow rate of the pressure drop ahead of the briquette front resulted in the initiation of an outburst. This meant that the investigated conditions *f*, *Mn* corresponded to a high level of outburst risk.

The outburst susceptibility was determined for the hubs of a two-dimensional parameter grid: porosity, the saturation pressure. During some auxiliary laboratory research (Skoczylas, 2009), the following relationships were determined for the investigated coal material: the relationship between the index of the intensity of methane desorption from the sample and the saturation pressure (Fig. 3), and the relationship between the firmness of the coal material and its poros-

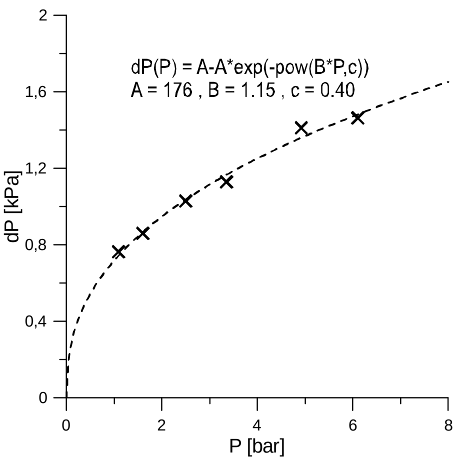

Fig. 3. The relationship between the index of the intensity of methane desorption from the sample and the saturation pressure

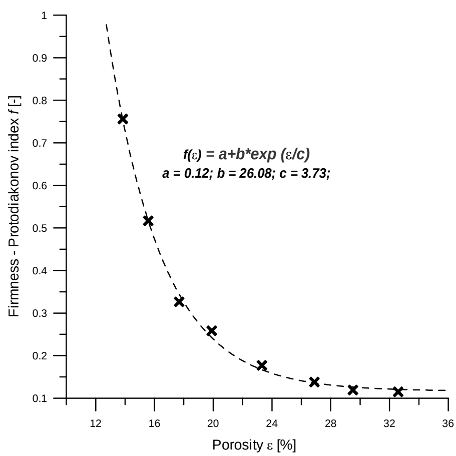

Fig. 4. The relationship between the firmness of the coal material and its porosity

ity (Fig. 4). Additionally, on the basis of the analysis of the results of measurements performed underground (discussed in detail in Section 3), the relationship between the methane capacity and the desorption intensity index for a selected coal seam was determined.

The direct measurement results (the minimum time constants of pressure drops ahead of the briquette front, resulting in an outburst) were normalized to the value of 100 and collected in Table 1. The Table served as a basis for generating a space of the outburst risk as a function of the parameters *f*, *Mn* (Fig. 5).

TABLE 1

Minimal time constants of the outburst induction rate, necessary for effective outburst initiation under laboratory conditions

		The methane content in coal *Mn* [m^3CH_4 / Mg_{coal}^{daf}]								
		4,2	**4,8**	**5,5**	**6,1**	**6,7**	**7,4**	**8,0**	**8,7**	**9,3**
firmness *f* [ ]	**1**	0,0	0,0	0,0	0,0	2,8	5,2	10,0	14,2	60,0
	0,8	0,0	0,0	0,0	0,0	10,1	11,9	12,5	35,0	77,0
	0,7	0,0	0,0	0,0	0,0	10,1	12,0	14,2	55,5	99,5
	0,6	0,0	0,0	0,0	0,0	10,2	12,2	20,0	60,0	99,5
	0,5	0,0	0,0	0,0	2,3	11,2	13,9	37,3	63,2	99,5
	0,4	0,0	0,0	0,0	3,0	12,7	58,9	72,5	99,5	99,5
	0,3	0,0	0,0	0,0	7,3	29,5	70,5	99,5	99,5	99,5
	0,2	0,0	0,0	9,2	30,7	52,0	81,0	99,5	99,5	99,5
	0,1	30,1	99,5	99,5	99,5	99,5	99,5	99,5	99,5	99,5

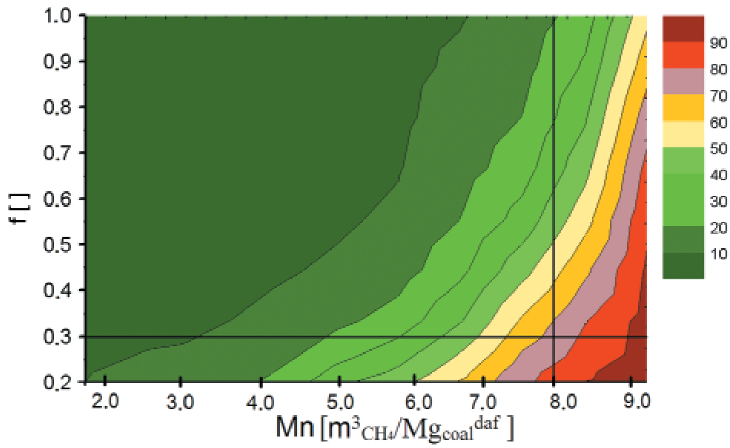

Fig. 5. The outburst risk as a function of the methane content in coal *Mn* and firmness *f*

The risk space has been depicted by means of an isohypse chart. An increase in the outburst risk (corresponding to an increase in the intensity of the outburst provocation necessary for a successful outburst initiation) is illustrated by the tonal transitions from green (minimum risk) through yellow (medium risk), to red (maximum risk). The obtained chart shows the state of the outburst risk as a function of firmness *f* and the methane capacity *Mn*.

Both the intuition of miners and the mining practice seem to confirm the validity of the obtained results. For the threshold limit value of firmness (*f* = 0.3) adopted by the Polish mining industry, the 50 percent outburst risk occurs at the Mn value of ca. 7 $m^3CH_4/Mg_{coal}{}^{daf}$. For the criterial value of the methane capacity oscillating around 8 [$m^3CH_4/Mg_{coal}{}^{daf}$], a similar level of risk occurs when the firmness of coal (*f*) is over 0.5.

Of course, the value of the isolines at 50 percent is conventional, and it is their shapes that should be interpreted rather than their values.

5. Recapitulation

The present paper discusses the results of laboratory and in situ research whose objective was to try and estimate the space of the outburst risk as a function of the parameters *f*, *Mn*. These parameters are among the most important indicators used to assess the probability of the outburst risk occurrence.

It can be stated with certainty that the actual changes in the level of the outburst risk are continuous in their nature (contrary to the threshold system). The developed risk space makes it possible to conduct an analysis that accounts for this fact. The level of risk is established on the basis of the analysis of the relationships between the methane capacity and firmness (contrary to the analysis in which the values of particular parameters are investigated separately).

Additionally, the proposed research makes it possible to follow the fluctuations in the level of risk, which is a source of additional knowledge on the upcoming risk trends – information no less important than the knowledge of the current risk level.

It is obvious that a more comprehensive analysis of the risk level requires investigating the relationships between particular indices, rather than analysing their values separately. The research presented here takes into account both the value of the „gas factor", i.e. the methane capacity, and the „mechanical factor", i.e. the firmness of coal. Neither the intuition of experienced miners nor the mining practice contradict the outcome of the analysis of the obtained laboratory results.

The presented results can help to improve the reliability of numerical experiments describing effects of the gas discharge in the area of mine workings (Skotniczny, 2009).

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