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THE RELATIONSHIP BETWEEN ROCK FRACTURING AND METHANE INFLOW INTO THE DRAINAGE HOLES ON THE BASIS OF COAL MINE MEASUREMENTS

RELACJA POMIĘDZY SZCZELINOWATOŚCIĄ GÓROTWORU A DOPŁYWEM METANU DO OTWORÓW ODMETANOWANIA NA PODSTAWIE POMIARÓW KOPALNIANYCH"

The present paper provides the results of measurements that were carried out in drainage holes in coal mines. The measurements involved determining the distribution of methane supplies into the holes in question, as hole as describing the variability of this parameter as a function of the hole's depth. Another investigated parameter was the fracturing of the rock and its changes during exploitation. The equipment used was an vane probe anemometer and an infrared digital introscope video camera. The measurements – which were conducted in several active drainage boreholes (below depression), ahead of the working longwall – enabled the researchers to identify both the spots of methane release and changes to the fracturing of the rock in relation to the distance to the longwall. Additionally, the changeability of the methane supply was demonstrated, together with the deepening of the rock fracturing conditioned by the decreasing distance between the longwall and a drainage hole. The calculated coefficients of correlation between the parameters describing the fracturing and the extent of methane inflow into the holes (established to be 0.90-0.99) prove that the measured factors are strongly interrelated.

Keywords: gas drainage, rock fracturing, methane hazard

W pracy przedstawiono wyniki pomiarów kopalnianych przeprowadzonych w otworach odmetanowania. Pomiary polegały na określeniu rozkładów dopływów metanu do wnętrza otworu odmetanowania wraz z opisem zmienności tego parametru w funkcji długości otworu. Wykonano również badania szczelinowatości górotworu. W badaniach zastosowano anemometryczną sondę skrzydełkową oraz kamerę wideo w podczerwieni. Pomiary wykonywano w kilku czynnych otworach odmetanowania (pod depresją) przed frontem eksploatowanej ściany. Pozwoliły one na określenie rozkładu dopływu metanu do otworów oraz zmian szczelinowatości górotworu w różnych odległościach pomiędzy otworami a ścianą. Pokazano zmienność dopływu oraz rozwój szczelinowatości górotworu wraz ze zbliżaniem się ściany do otworu odmetanowania. Obliczone współczynniki korelacji pomiędzy parametrami opisującymi szczelinowatość a wielkością dopływu metanu do otworów, na poziomie od 0.90 do 0.99 wskazują na bardzo silną zależność miedzy zmierzonymi parametrami.

Słowa kluczowe: odmetanowanie, szczelinowatość górotworu, zagrożenie metanowe

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1. Introduction and objectives

The paper deals with the issues of methane supply into drainage holes and the impact that this phenomenon has on rock fracturing. In engineering, various systems of drainage are used, which entail both pre-mining drainage and post-mining drainage (performed on gob area) (Jenkins & Frazier, 2010; Karacan & Luxbacher, 2010). Information on modeling and control of methane release can be found, among others, in papers by Karacan (2009), Krause (2009).

Karacan et al. (2007) and Kirchgessner et al. (2002) provided a review of the most common borehole mining methods applied in the process of degasification of coal seams and longwall areas of gas release, presenting some of the advantages and disadvantages of each method. Additionally, Karacan et al. (2007) aimed to investigate the impact of the spacing of boreholes during horizontal drainage, and analyze the effect of drainage duration upon the reduction of methane content in the excavation longwall of the Pittsburgh coal seam.

There are a lot of publications concerning research into simulated boreholes in coal seams located in various coal basins (Cameron et al., 2007; Holditch, 1990). All of them recommend specific strategies for borehole spacing and drilling.

More and more often, the rock structure is examined by means of the introscopic (endoscopic) methods, involving visual penetration of the boreholes with a camera sensitive to infrared light or the visible light spectrum. Stopyra et al. (1998) and (Pierszalik, 2010) describe an introscopic method involving the use of an infrared camera, due to which it is possible to determine not only the extent of fracturing, but also the dimensions of the fracturing zone surrounding an excavation. The practical application of the method is examining boreholes located in the direct vicinity of excavation. The distribution of fissures in rocks surrounding excavations – and, more precisely, the characteristics of natural fracturing of rocks – is the subject matter of the works by Kabiesz and Patyńska (2009), who described the distribution of rock fracturing along a given, examined borehole, presented the results of fracture size measurements, and evaluated the linear fracture density. The results of earlier, *in situ* investigations **(**Kidybiński & Siemek, 2006), showed that the fracturing of the rocks in the vicinity of underground galleries deepens with time – and its final range depends on the shape and dimensions of the heading, the strain state of the rock, and, above all, the type of rocks. Rock fracturing plays an important role in issues of shale gas extraction (Nagy & Siemek, 2011) and in prevention of gas and coal outbursts (Wierzbicki & Młynarczuk, 2006, 2013).

Relevant works dealing with studies carried out in drainage holes do not mention measurements or analyses of methane releases occurring at various depths of the hole; therefore, it seems fair to assume that so far such procedures have not been performed. A further implication is that no one has ever attempted to determine the correlation between the distribution of the methane release along a drainage hole and the fracturing. The present paper provides a truly innovative approach to the issue of methane outflow from deep drainage holes drilled in the exploitation longwall. The intention is to present the results of studies into the distribution of methane inflow into drainage holes, as hole as the distribution of rock fracturing. The studies will be based on penetration of drainage holes by means of an infrared camera. Also, gaseous and structural parameters of the rock will be statistically correlated.

2. Measuring equipment

2.1. Anemometer for measuring the distribution of the volumetric flow rate of gas in drainage holes

The measurements were carried out by means of a vane sensor with a built-in inductive sensor described in (Kruczkowski, 2012). An anemometer of this type is resistant to changes of temperature, humidity, dusting, and the density of the medium, which are likely to occur inside a drainage hole. The range of temperatures in which it can be applied is from – 20°C to 70°C, and the maximum humidity that the device can tolerate is 100% RH.

A complete system of an anemometric sensor is depicted in Fig. 1. The electronics is protected by a hermetic casing with a covered socket for charging the battery (Fig. 2).

Flowmeter was built in Laboratory of Mine Ventilation of Strata Mechanics Research Institute specially for this measurements.

Fig. 1. An anemometric vane sensor (Kruczkowski, 2012)

Fig. 2. An anemometr for measuring the distriubtion of the volumetric flow rate – a general view

2.2. Introscopic camera

An introscopic infrared camera was built for the purpose of registering the image of the inside of a drainage hole. The device is depicted in Fig. 3. The building elements used in the construction process were:

- − a CCD camera, which makes it possible to register video sequences in a HDTV 720p resolution (1280 × 720) with a speed of 60 FPS (frames per second), or in a HDTV 1080p resolution (1920 × 1080) with a speed of 30 FPS,

- − a set of lenses and converters for obtaining a sharp image in a hole, of a diameter of 75 mm (the camera's field of vision has the extent of ca. 30 × 20 mm),
- − a set of diodes serving as a source of illumination,
- − a lithium-ion battery,
- − building blocks.

The film registered by the camera is recorded on an SD memory card with a storage capacity of 8GB and a video compression standard of H.264. The whole system operates in infrared light in an autonomic fashion, using internal powering. It does not require any electrical impulses.

Fig. 3. An introscopic camera in a hermetic casing

The angular resolution of the camera, estimated under laboratory conditions, is not less than 20 line pairs per millimeter. More detailed information regarding the camera can be found in the paper by (Dziurzyński et al., 2012).

3. Measurements performed in mines

Six series of measurements were performed (in four drainage holes). Each of them involved measuring the supply of methane in particular sections of the holes, and, subsequently, registering the images with an introscopic camera placed within a given hole.

Fracturing and the release of gas into drainage holes were measured in the B-3a gallery of the 405/1łg coal seam in the "Zofiówka" mine in south part of the Upper Silesian Coal Basin (fig. 4). The B-3a longwall in the 405/1łg coal bed is ventilated in a U system. The average absolute methane emission in the ventilation area during the measurements was 8.03 m^3/min. In the vicinity of the B-3a longwall, an active degasification process was carried out by means of drilling, in an ongoing way, drainage holes from the B-3a gate, ahead of the active longwall. The distance between consecutive clusters was 18.0 m. At every drilling post, a cluster of three drainage holes were drilled.

The lithology of the roof rocks is depicted in Fig. 5. The dominant components of this geological description are sandstones and mudstones. Within the distance of ca. 34 m from the roof of the excavation, there is a layer of coal seam less than 1 m thick. The geometric parameters of the drainage holes where the measurements were carried out are presented in Table 1.
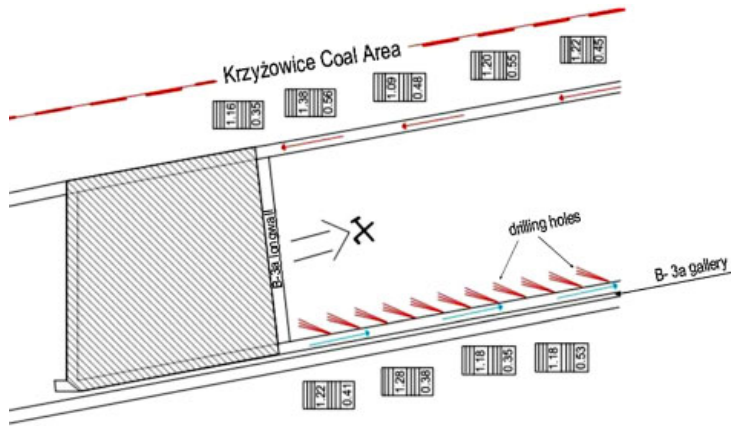
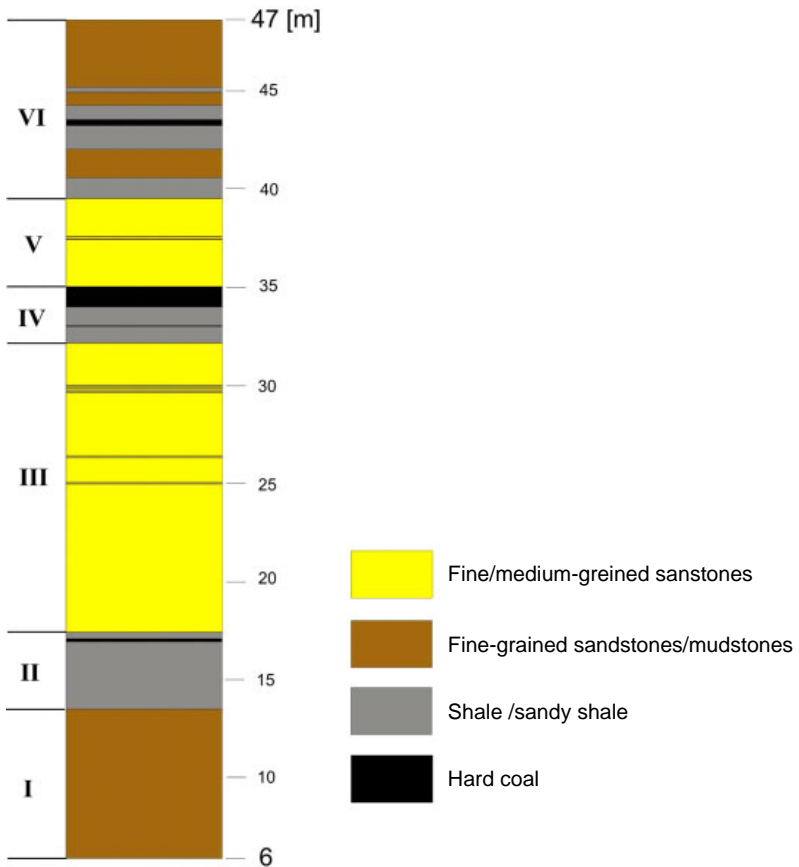Fig. 4. A fragment of a plan of the 405/1 coal bed in the „Zofiówka" mine

Fig. 5. A lithologic description of the Załęże rock mass above the 405/1łg coal bed (Dziurzyński et al., 2012)

The parameters of the examined drainage holes

Hole no.	Hole length (m)	Horizontal angle (°)	Vertical angle (°)
1	98	32	23
2	80,5	28	20
3	99	24	28
4	91,5	28	28

The measurements were carried out during the exploitation of the longwall, in six stages. By "stage" we shall understand a day when underground measurements were performed in at least one drainage hole. The distances between the inlets of particular holes and the longwall front L, at the consecutive stages of the works, are presented in Table 2.

Distances between the drainage holes and the longwall, for each stage of the measurements

Stage no.	Hole no.	L (m)	Stage no.	Hole no.	L (m)
1	1	67	5	1	32
2	1	57		2	50
	2	75		3	68
3	1	46	6	2	36
	2	64		3	54
	3	82		4	72
4	1	42			
	2	60			
	3	78			

3.1. Measurements of the distribution of gas supply into drainage holes

The measurements of the methane release were carried out in active drainage holes (under depression). In order to ensure a controlled move of research probes along a hole, special wedges with a deflection roller were designed. They were subsequently bolted to the bottom of the borehole by means of drilling rods. A string on a deflection roller made it possible to move the devices along the hole. Due to the conditions under which the measurements were carried out, the casing pipe was equipped with culverts to ensure its tightness.

Fig. 6. provides an example of direct registration of a change in the flow rate as a function of time, for one of the measurements performed. The particular metric values, marked on the diagram, represent spots at which the measuring probe was stopped so that the flow rate could be measured. It was necessary to wait ca. 3 minutes to allow the flow rate to stabilize. It was assumed that the flow rate at a given measuring spot was the mean value of the results obtained during the last 60 seconds of a measurement performed at a given depth.

Each time, the obtained results (the flow rates) were converted into the volumetric values (with the results of the anemometric probe adjustment taken into account) and into values corresponding to laboratory conditions (the temperature of the gas released – i.e. 35°C – included).
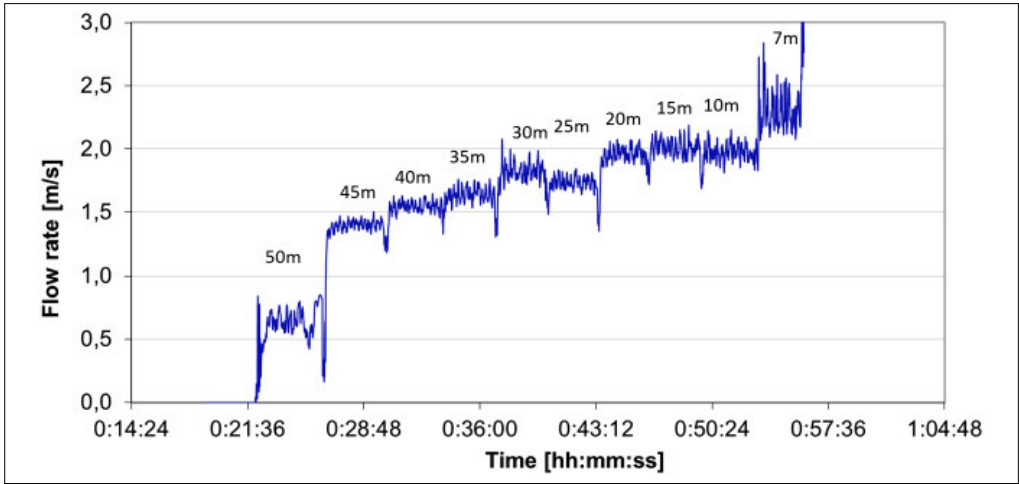
Fig. 6. An example of a direct result of the flow rate measurement performed in a drainage hole

As the concentration of CH_4 was measured, it was possible to convert the value of the release into the one corresponding to pure methane. The diagrams in Fig. 7-10 show the supply of the gas mixture into particular drainage holes as a distance function, taking into account the position of each measuring spot in relation to the inlet of the hole. The lithologic blocks singled out in the geological description were also presented (cf. Fig. 6).

The measurements of the gas releases were performed starting with the spot where the casing pipe ended (ca. 7 meters from the excavation sidewall). Each curve in a diagram presents changes in the gas release registered during consecutive measurements, performed at different times (and,
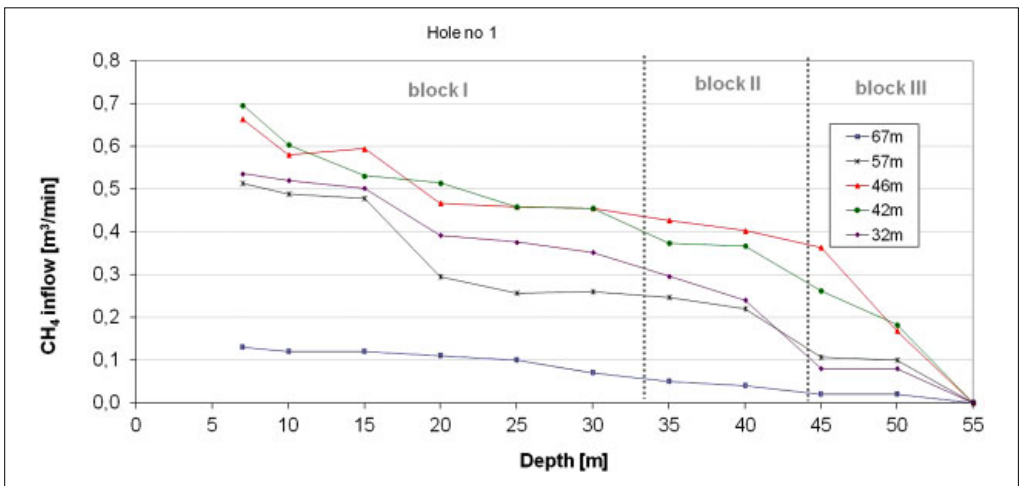

Fig. 7. A supply of gas mixture into hole no. 1, for particular lithologic blocks
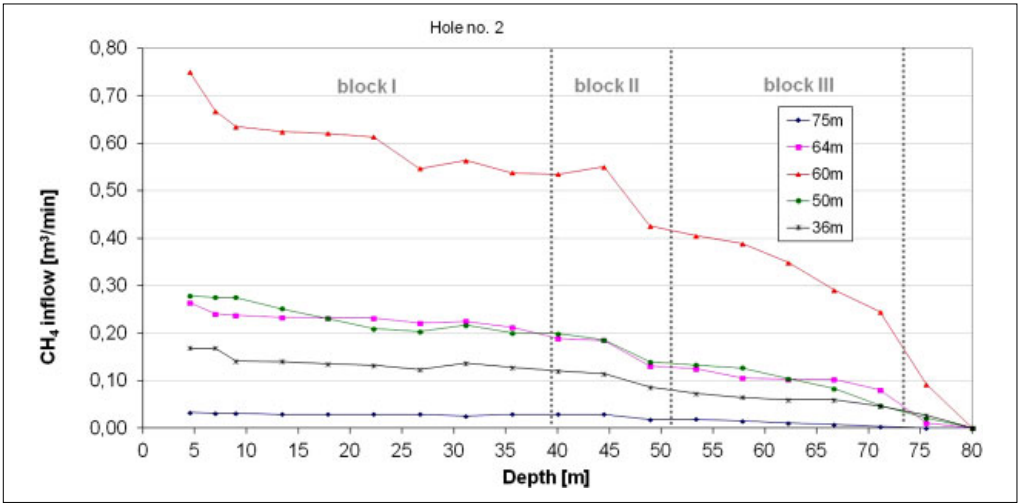
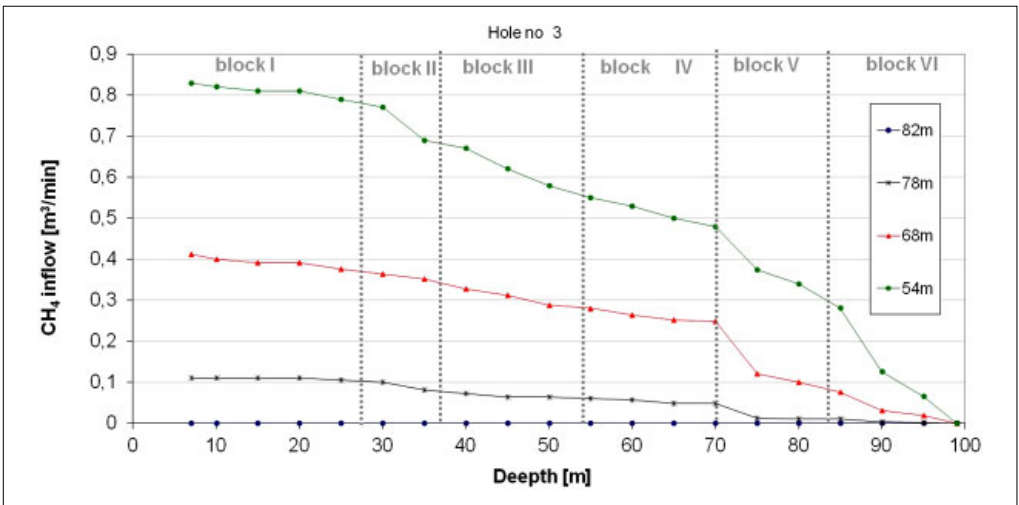Fig. 8. A supply of gas mixture into hole no. 2, for particular lithologic blocks

Fig. 9. A supply of gas mixture into hole no. 3, for particular lithologic blocks

what follows, at various distances from the front of the longwall). The first measurable supply of gas into the hole occurs when distance between the inlet of the hole and the longwall front is ca. 78 m. In such a case, the end of hole was 12.5 m behind the longwall front. The vertical distance between the end of hole and the roof of drift was ca. 46.5 m.

Fig. 11 is a diagram which shows the changes in the gas mixture and pure methane releases at the outlet of the hole, as a function of the distance from the longwall. On the horizontal axis,
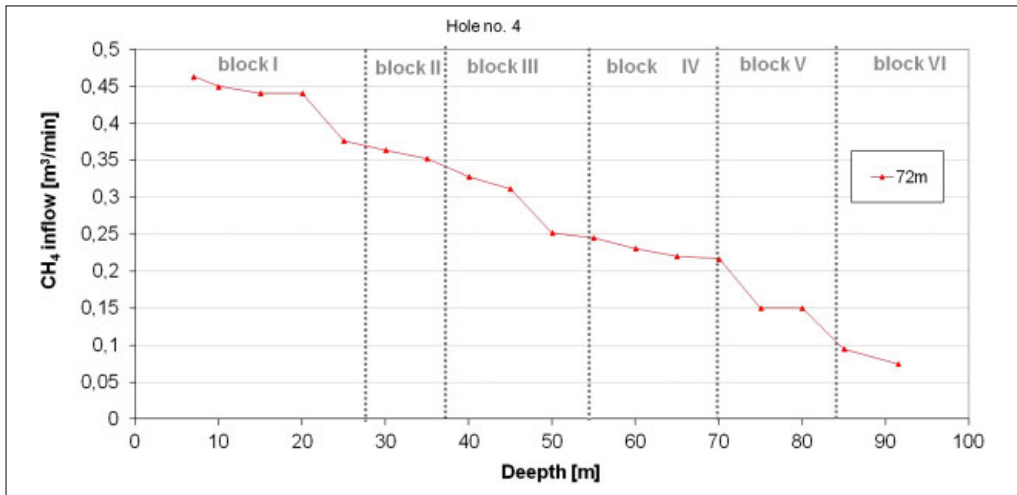
Fig. 10. A supply of gas mixture into hole no. 4, for particular lithologic blocks

the horizontal distances between the bottom of the hole and the longwall front were marked. The below zero values indicate that the bottom of a given hole is behind the longwall front.

Taking into consideration the present conditions in mines and the degasification system being used, it is to be concluded that the maximum releases occur when the longwall front is located in the direct vicinity of the bottom of a drainage hole. Qualitatively, these results correspond with the ones obtained by Frejowski and Drzewiecki (2008).
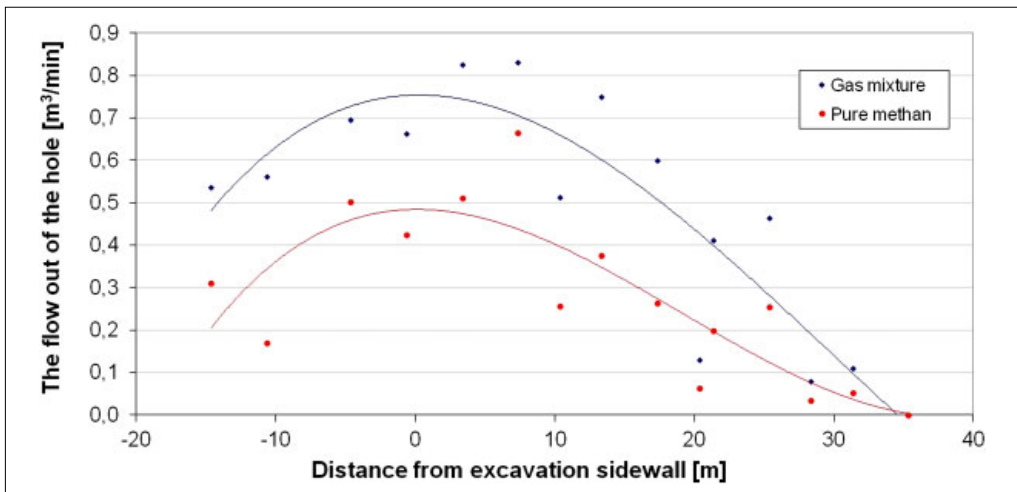

Fig. 11. Changes in the gas mixture and pure methane releases as a function of the distance between the hole outlet and the longwall

3.2. Measuring the rock fracturing in the vicinity of drainage holes

A measurement of the rock fracturing was performed each time after the gas release from a drainage hole was measured. The equipment used in the process was an introscopic camera. After the camera was moved by 1 meter, it was stopped for several seconds, which made it possible to identify its location in relation to the hole inlet.

There are a lot of scientific works that deal with classifying rock masses on the basis of their fracturing – some examples are (Kidybiński, 1982; Pinińska 1994). In the present studies, the classification proposed by (Młynarczuk & Wierzbicki, 2012) was applied, which takes into account both the width of the fissures visible in the video material and their number. The details are provided in Tab. 3.

The application of the above-mentioned classification system, together with the analysis of the video material registered during the scanning of drainage holes, enabled the Author to single out fracture fractions for particular depth values, and for each particular stage of the works (i.e., for different distances from the longwall front). As an example, the Author shall analyze the case of hole no. 1, for which four scanning procedures were performed. The depth of the first two scans was 54 m, and the depth of the next two scans was 47 m (as far as the original depth of the hole is concerned, which was ca. 100 m, these were the only two sections that could be penetrated with the camera). It ought to be mentioned that, during the fifth measurement performed within the hole, the camera was lost. The results of the fracturing measurements carried out in particular holes are shown in Fig. 12-15.

TABLE 3

Suggested classification for the description of the state of fracturing, as seen in video materials

Fraction	Description of fractures (in relation to a 1m measurement section, i.e. 300 video frames)
0	Lack of fractures
1	Small-width fractures (up to 0.5 mm), observed sporadically, on random frames
2	Small-width fractures (up to 0.5 mm), observed on more than 33 percent of frames
3	Medium-width fractures (up to 2.5 mm),observed sporadically, on random frames, **or:** small-width fractures (up to 0.5 mm), observed on more than 80 percent of frames
4	Medium-width fractures (up to 2.5 mm), observed on more than 33 percent of frames
5	Wide-width fractures (over 2.5 mm), observed sporadically, on random frames, **or:** medium-width fractures (up to 2.5 mm), observed on more than 80 percent of frames
6	Wide-width fractures (over 2.5 mm), observed in more than 33 percent of frames
7	Areas characterized by a large network of fractures (rubble-like), observed sporadically, on random frames **or:** wide-width fractures (over 2.5 mm), observed on more than 80 percent of frames
8	Areas characterized by a large network of fractures (rubble-like), observed in more than 33 percent of frames
9	Areas characterized by a large network of fractures (rubble-like), observed in more than 80 percent of frames

In the diagrams above, the vertical blue lines represent the borderlines of the lithologic zones.
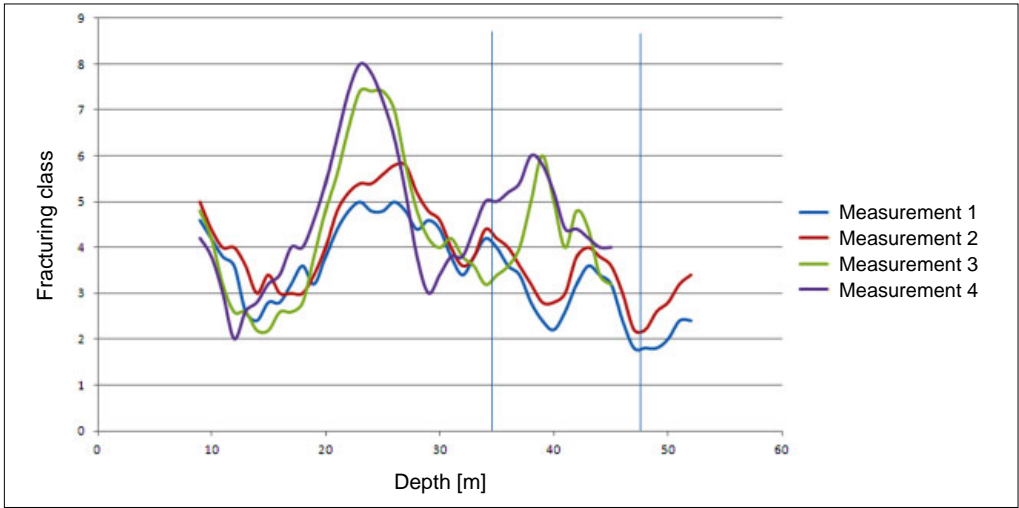
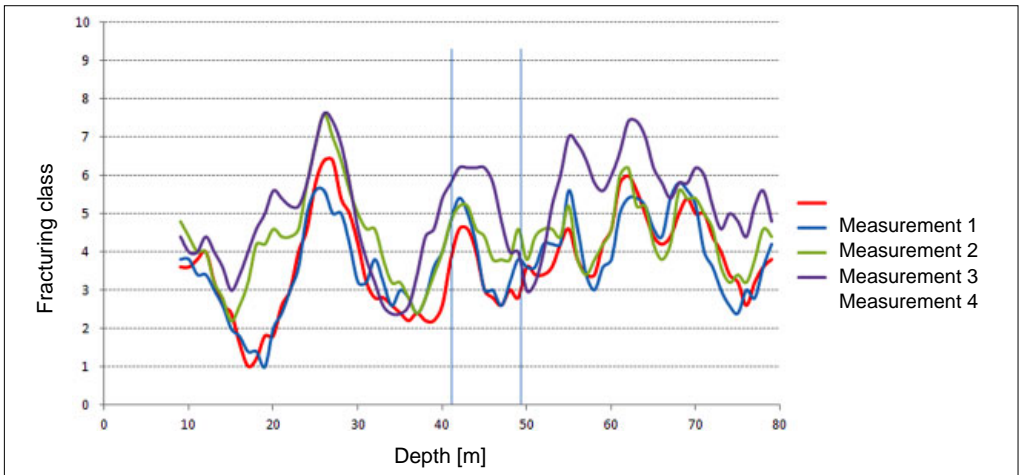Fig. 12. Hole no. 1 – the results of the fracturing measurements

Fig. 13. Hole no. 2 – the results of the fracturing measurements

The observed increase in fracturing may be attributed to the lithologic profile of the rock, obtained in the course of research carried out by means of a introscopic camera applied in white light (Dziurzyński et all., 2012). According to this lithologic profile, 14 meters above the excavation roof, there are shales, claystones, carbonaceous shales, and some scattered coal matter. Taking into account the drilling angles for particular drainage holes, one has to observe that the desired vertical distance for hole no. 1 should be reached at the 36th meter down the hole; for hole no 2. – at the 41st meter down the hole; for holes no. 3 and 4 – at the 30th meter down the hole.
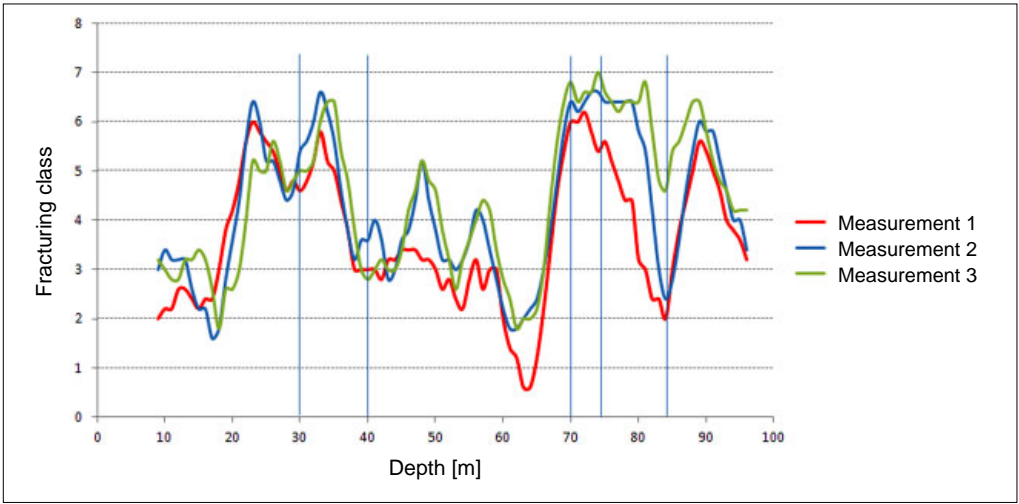
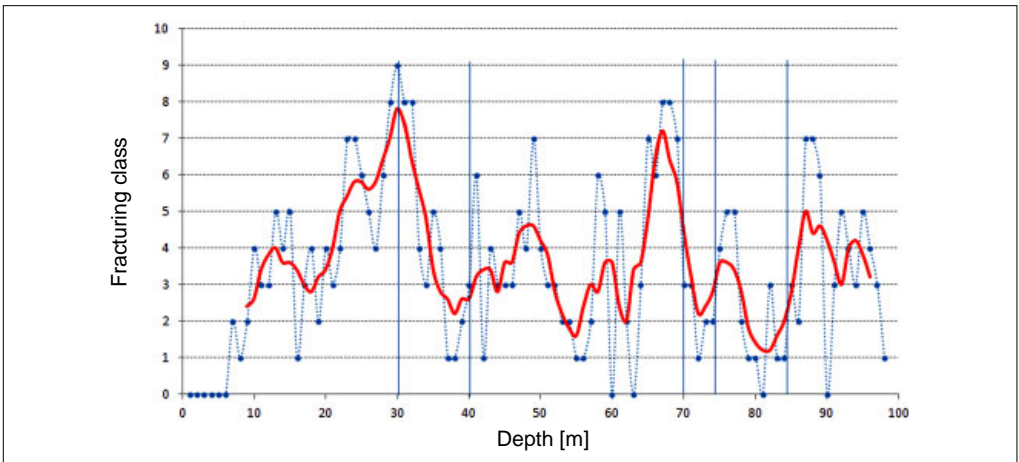Fig. 14. Hole no. 3 – the results of the fracturing measurements

Fig. 15. Hole no. 4 – the results of the fracturing measurements

Increases of fracturing observed in holes 3 and 4, at the depth of ca. 75 m (the vertical distance being 35 m), correspond to the depth at which the coal of the thickness of less than 1 m occurs.

Fig. 16 presents fracturing of the rock as a function of the distance from the longwall and the excavation sidewall. The figure was compiled from the results of the fracturing measurements performed during the scanning of hole no. 1 and a map showing the degree of fracturing at a given depth (expressed in meters), together with the position of a given spot in relation to the longwall front and the excavation sidewall at the moment when the measurement was carried out. The fracturing of the rock increases as the distance from the longwall front diminishes.
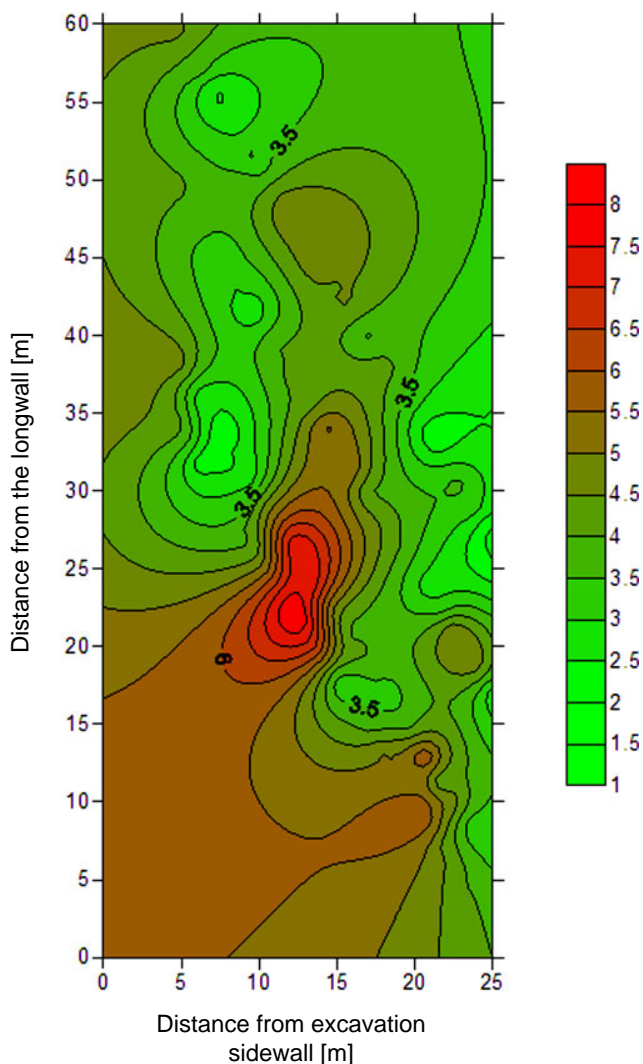
Fig. 16. Fracturing of the rock as a function of the distance from the longwall and the sidewall
– the relationship described as a result of 4 measurements in hole no. 1

4. Identifying the relationship between the rock fracturing and the methane release

Due to the obtained measurement results, it was possible to determine the correlation between the parameters describing the fracturing of the rock and the extent of the supply of methane into drainage holes, in relation to dynamic mining circumstances (advancing of the longwall). Table 4 includes coefficients of the fracturing-release correlation, for all the measurements performed.

Such correlations were established for each of the performed measurement series (fracturing-release), for various distances of the holes from the longwall. It was determined that there exists a very strong correlation between the presented rock characteristics, which can be described by means of proper correlation coefficients, falling within the scope of 0.90-0.99.

<div align="right">TABLE 4</div>

Coefficients of correlation between the gas release (m^3/min) and the total of the fracturing coefficients

	Hole no. 1	Hole no. 2	Hole no. 3	Hole no. 4
Measurement 1	0,98	0,95	–	0,99
Measurement 2	0,96	0,97	0,97	–
Measurement 3	0,90	0,98	Fracturing not measured	–
Measurement 4	0,96	Fracturing not measured	0,98	–
Measurement 5	Fracturing not measured	0,97	–	–

5. Summary and conclusions

As part of the underground research works, a series of studies were performed, which involved measuring of methane supply into drainage holes and analyzing the fracture networks surrounding the holes. The measurements of the methane supply were carried out by means of an introscopic measuring probe which registers the rotational speed of the measuring vane. The rotational speed is proportionate to the flow rate of gas within a drainage hole. Measuring the concentration of methane, in turn, made it possible to calculate the releases of pure methane flowing out of particular holes.

Registering of the fracture networks was based on an analysis of the video sequences captured by an introscopic camera in infrared, in the same drainage holes, right after the gas release from the hole was measured. For the purpose of the description and analysis of the obtained results, the classification of fractures provided by (Młynarczuk & Wierzbicki, 2012) was applied. According to this classification, there are ten fracture fractions, to which particular fragments of the analyzed video sequences were assigned.

The obtained results paved the way for identifying the correlation between the parameters describing the rock fracturing and the extent of the methane supply into particular sections of drainage holes.

The most important conclusions are as follows:

− Measuring the supply of gas and the fracturing inside the drainage holes up to 100 m deep was a substantial challenge, both in practical and organizational terms. The measurements were performed in active drainage holes (under depression), during exploitation works, which required interference with the drainage system (such as temporal deactivation of particular holes). In such circumstances, ensuring safety of the researchers proved to be a task of vital importance.

− A set of measurement results for the flow rate of the gas mixture in drainage holes were obtained, together with corresponding video sequences making it possible to determine

the rock fracturing. The flow rates were converted into gas releases, and correlated with the parameters describing the rock fracturing. The correlation results testify to a strong relationship between the methane supply and the fracturing of the rock.

− It was demonstrated (in a quantitative manner) that the fracturing of the rock depends also on mining conditions. A change in the value of the fracturing coefficient (which increased as the distance between the longwall front and the drainage hole diminished) was observed and described.

− The analysis of related scientific works proves that the conducted research is a pioneering project, as yet untackled by the international mining industry.

References

Cameron J.R., Palmer I.D., Lukas A., Moschovidis Z.A., 2007. *Effectiveness of horizontal holes in CBM*. International Coalbed Methane Symposium, Paper 0716. The University of Alabama, Tuscaloosa, AL.

Dziurzyński W., Wierzbicki M., , Skoczylas N., Kudasik M., Kruczkowski J., Kozielska R.: *Studies on the inflow methane with an indication of pressure distribution in the drainage holes*, Report on the strategic research project „Improving safety in mines", Task 4.3.2 (in polish).

Frejowski A., Drzewiecki J., 2008. *Wpływ odległości frontu eksploatacyjnego od otworów drenażowych na proces odmetanowania górotworu*. Prace Naukowe GIG. Górnictwo i Środowisko, GIG.

Holditch S.A., 1990. *Completion methods in coal seam reservoirs*. Ann. Tech. Conf. New Orleans, LA. SPE 20670. September 1990.

Jenkins R.B., Frazier P., 2010. *High-resolution remote sensing of upland swamp boundaries and vegetation for baseline mapping and monitoring*. Wetlands 30 (3), 531-540.

Kabiesz J., Patyńska R., 2009. *Badania zasięgu i intensywności strefy spękań wokół chodnikowych wyrobisk korytarzowych*. Górnictwo i Geoinżynieria 33 Zeszyt 1.

Karacan Ö., 2009. *Reservoir engineering considerations for coal seam degasification and methane control in underground coal mines*. Mine ventiltion, vol. 1.

Karacan Ö., Diamond W.P., Schatzel S.J., 2007. *Numerical analysis of the influence of in-seam horizontal methane drainage boreholes on longwall face emission rates*. International Journal of Coal Geology 72, 15-32.

Karacan Ö., Luxbacher K., 2010. *Stochastic modeling of gob gas venthole production performances in active and completed longwall panels of coal mines*. International Journal of Coal Geology 84 (2), 125-140.

Kidybiński A., 1982. *Podstawy geotechniki kopalnianej*. Wydawnictwo „Śląsk", Katowice.

Kidybiński A., Siemek J., 2006. *Podziemne magazyny gazu w zaniechanych kopalniach węgla*. Główny Instytut Górnictwa, Katowice.

Kirchgessner A.D., Masemore S.S., Piccot S.D., 2002. *Engineering and economic evaluation of gas recovery and utilization technologies at selected US mines*. Environmental Science and Policy 5, 397-409.

Krause E., 2009. *Prediction of methane emissions into longwall workings during mining by means of a cutter-loader*. Mine ventiltion, vol. 1.

Kruczkowski J., 2012. *Metoda pomiaru strumienia objętości gazu w otworach odmetanowania*. Translactions of the Strata Mechanics Research Institute, Vol. 14, No 1-4. Kraków.

Młynarczuk M., Wierzbicki M., 2012. *Badania szczelinowatości górotworu wokół otworu odmetanowania na podstawie analizy zapisów z kamery introskopowej*, Translactions of the Strata Mechanics Research Institute, Vol. 14, No 1-4. Kraków.

Nagy S., Siemek J., 2011. *Shale Gas in Europe: the state of the technology – challenges & opportunities*. Arch. Min. Sci., Vol. 56, No 4, p. 727-760.

Pierszalik R., 2010. *Badania introskopowe przy użyciu sondy ABS – możliwości badawcze oraz uwagi dotyczące użytkowania*. Przegląd Górniczy, Vol. 66, No. 11.

Pinińska J., 1994. *Właściwości wytrzymałościowe i odkształceniowe skał. Część I: Skały osadowe regionu Świętokrzyskiego*, Wyd. Uniwersytetu Warszawskiego, Warszawa.

Stopyra M. Rak Z. Stasica J., 1998. *Possibilities of testing of rock structure using methodology supported by infrared introscopy*. Cuprum, nr 8.

Wierzbicki M., Młynarczuk M., 2006. *Microscopic analysis of structure of coal samples collected after an gas and coal outbursts in the gallery D-6, coal seam 409/4 in the „Zofiówka" coal mine (Upper Silesian Coal Basin)*. Arch. Min. Sci., Vol. 51, No 4, 577-588

Wierzbicki M., Młynarczuk M., 2013. *Structural aspects of gas and dolomite outburst in "Rudna" copper mine, Poland*. Int. Journal of Rock Mech. and Mining Sciences, Vol. 57, p. 113-118