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FORECAST OF THE MAXIMUM METHANE CONCENTRATION IN THE LONGWALL OUTLET AND IN THE VENTILATION ROADWAY. CASE STUDY

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Abstract:
The mining process of the coal seam wall is accompanied by the release of methane into the mine atmosphere. This process is highly variable and depends on the methane content in the seam and the methane saturation of the rocks surrounding the seam. This is the specificity of the Polish hard coal mining industry. In the article, prognostic formulas for the maximum methane concentration at the outlet of the longwall ventilation gallery were developed. In the presented article, these formulas were used to predict methane concentration at the longwall outlet and in the ventilation gallery at a distance of up to 10 m in front of the longwall. In order to assess the accuracy of the forecasts, their results were compared with the forecast at the exit of the ventilation roadway. The obtained results are so accurate that it is worth repeating this type of check also using measurements in other longwalls. It will allow to reduce the risk of methane explosion during operation.

Key words: *methane content, max methane concentration, methane content forecasts, methane content changes, analysis of measurement data and forecasts*

INTRODUCTION

Hard coal mining is one of the most dangerous processes, which results from the environmental conditions in which it is carried out. Among the many natural hazards occurring in the process of underground mining, the methane hazard is particularly dangerous and causes large material losses and poses a huge threat to the life and health of employees [1, 2, 3, 4].

Methane in coal mines occurs as a gas associated with coal through physical and chemical adsorption, as a free gas and as a gas dissolved in water [5, 6, 7].

Chemisorption consists in the transition of electrons between methane and the surface of the carbon skeleton. This process involves the formation of a chemical relationship between coal and the first layer of adsorbed methane [8]. This reaction is reversible under the right conditions, but this is difficult to achieve.

Physical adsorption is caused by intermolecular forces (mainly van der Waals forces) [7, 8, 9]. On the surface of the carbon skeleton, a layer with a thickness of one or several diameters of a methane molecule is formed. Physical adsorption is an easily reversible phenomenon.

Free methane is found in mesopores, micropores and macropores of the coal skeleton, in fissures in the coal, in the pores of mineral substances in the coal seam and also in the pores and fissures of the rocks surrounding the seam, especially in sandstones.

The largest amount of methane in a coal seam is accumulated on the inner coal surface [6, 7, 9, 10].

As a result of the pressure difference between the methane contained in the coal pores and the air pressure in the mining excavations, free methane flows into the mine atmosphere. Free gas losses in the pores are replenished

with methane from desorption. Of course, with the loss of methane in coal, its pressure in the coal pores decreases.
The methane hazard is one of the most widespread hazards in Polish coal mining [11, 12, 13]. The flammability and explosiveness of methane make this gas a huge problem for the safety, continuity and efficiency of coal mining. Events related to the methane hazard are most often catastrophic and result in huge material and very often personal losses [14, 15]. The authors [25] cite the same risks for copper ore mining. The intensity of the methane hazard in mines is assessed on the basis of forecasts of methane release to excavations or on the basis of forecasts of methane concentration in excavations [16, 17, 18, 19, 20]. In order to reduce the negative impact of methane on the mining process, many different types of activities are undertaken, the general purpose of which is to prevent the occurrence of dangerous concentrations of this gas in the mining area. These activities focus mainly on obtaining methane from the rock mass through drainage holes connected to the methane drainage system made in the rock mass, as well as capturing methane from behind the dams separating goaf from active excavations, and the appropriate selection of ventilation parameters in mining excavations so that critical concentrations of this gas do not occur [4, 18, 21, 22].
The commonly used methods of diagnosing and forecasting methane concentrations most often refer to their average values in a given excavation. However, the instantaneous values of methane concentration in many places of excavations reach or even exceed the limit values. This leads to the interruption of the exploitation process for the time limit values are reached. They disrupt the continuity of coal exploitation and reduce its efficiency. In the event of exceeding the permissible concentrations of methane, the electricity is turned off, thanks to which the initial ignition or explosion of methane resulting from the operation of electrical machines and devices is avoided. However, these unplanned downtimes interrupt the continuity of coal mining, which significantly reduces the working time of machinery and equipment, and subsequently reduces the efficiency of their use [2, 15, 21, 23, 24].
This article applies to longwall run in a "U" pattern from the field boundaries. The highest values of methane concentration in longwalls exploited in the "U" system, in the direction from the field boundaries, are recorded in the outlet section of the longwall and in the ventilation roadway. Mining regulations oblige to place a minimum of four sensors in this area, an example of their location is shown in Figure 1. The sensors are marked as CSM-1, CSM-2, CSM-3, CSM-4.
The fifth mandatory methane concentration sensor (CSM-5) in the ventilation roadway is placed, in accordance with the mining regulations, at the exit of the ventilation roadway at a distance of 10-15 m from the intersection with another roadway (in the case discussed in the article it was a slipway).
Figure 1 also shows auxiliary means of ventilation: air duct and ventilation partition. In the described case, no ventilation partition was used, but only an additional supply of fresh air through an air duct. The location of the air duct outlet is adjusted to the location of the highest methane concentration. In the discussed case, the outlet was located a short distance from the collapse line of the roadway, which meant that the CSM-2 sensor showed methane concentration not higher than 0.2% CH_4.
The CSM-1 sensor should be located in the longwall, in the place of the highest concentration of methane, at a distance of up to 1/3 of the length of the longwall from the ventilation roadway (above the longwall). Most often it is suspended in the immediate vicinity of the return drive of the face conveyor, which was the case in the case presented in the article.

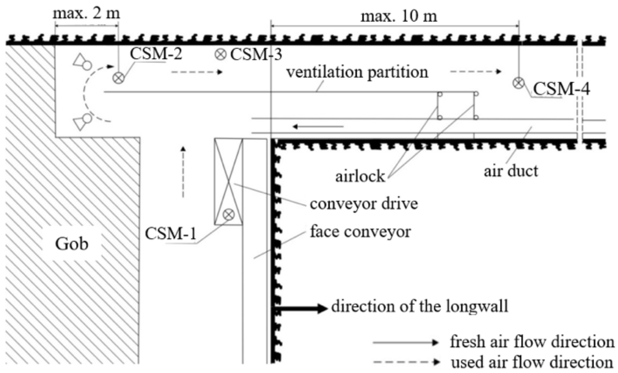

Fig. 1 Example arrangement of sensors and auxiliary ventilation devices at the outlet from a ventilated longwall in the "U" pattern

Figure 2 shows an exemplary view of a fragment of the result file of measurements carried out by one of the methane meters located in the examined exploitation area.

MEASUREMENTS OF SENSOR No. 533
Mine: HASO SC
Print date: 2.05.2021; 7:31:13
Report period: 20.10.2018; 6:00:00 - 22.11.2019; 6:00:00
Range: 0.00%CH4 - 5.00%CH4
Place of installation: out. f. rec. longwall

Measurements: all

Start time	Measurement	Measurement time	Statuses
23.11.2019 20:21:54	0.4%CH4	0:25:06	
23.11.2019 20:21:52	0.3%CH4	0:00:02	
23.11.2019 10:56:08	0.4%CH4	9:25:44	
23.11.2019 10:55:58	0.5%CH4	0:00:10	
23.11.2019 09:11:14	0.4%CH4	0:15:02	

Fig. 2 View of a part of the methane sensor file with recorded methane concentrations
Source: own study based on data from a mining company.

The measurement system records the methane concentration so that the most recent measurement is stored at the top. The "Start time" column contains the date of methane concentration measurement and the start time of the measurement. In the "Measurement" column, the measured value of methane concentration was recorded with an accuracy of 0.1% CH_4. The entry in the "Measurement time" column informs how long the methane concentration had the value recorded in the "Measurement" column. In "Statuses" there are comments regarding the correctness of measurements, warnings about methane concentration approaching the limit value, methane concentration measurements during checking the correct operation of the sensor, etc.

The article uses measurement data from sensors CSM-1 (at the longwall outlet), CSM-4 (located in the ventilation roadway at a distance of up to 10 m in front of the face of the longwall) and CSM-5 (in the ventilation roadway, 10-15 m from the intersection with the slipway).

Using the PROGMET program developed at the Silesian University of Technology, the average, minimum and maximum concentrations of methane were calculated on the basis of measurement data sets in the calculation day, which started at 6:00:00 a.m. of the current day and ended at 6:00:00 a.m. on the next day. In addition, the program calculates the durations (in seconds) of methane concentrations of a specific value in the range from 0% to 2%. Methane concentration ranges are given with an accuracy of 0.1% from 0.0% CH_4 to 2% CH_4. Times of occurrence of methane concentrations higher than 2% are included in the 2% concentration range.

The measurement data set referred to the period from October 20, 2018 to November 22, 2019, i.e. to 398 days.

STATISTICAL CHARACTERISTICS OF THE MAXIMUM METHANE CONCENTRATION

There are papers [18, 19] present prognostic formulas for the maximum methane concentration developed on the basis of measurement data from 10 longwall regions, referring to the outlet from the ventilation roadway. In the presented article, the measurement data was processed in the manner described in Chapter 1, in order to check the applicability of these formulas to forecasts of maximum methane concentration values, measured with sensors located:

- at the outlet from the ventilation roadway, 10-15 m from the intersection with a slipway,
- in the ventilation roadway, up to 10 m in front of the face of the longwall,
- in the longwall, near the upper (return) drive of the face conveyor.

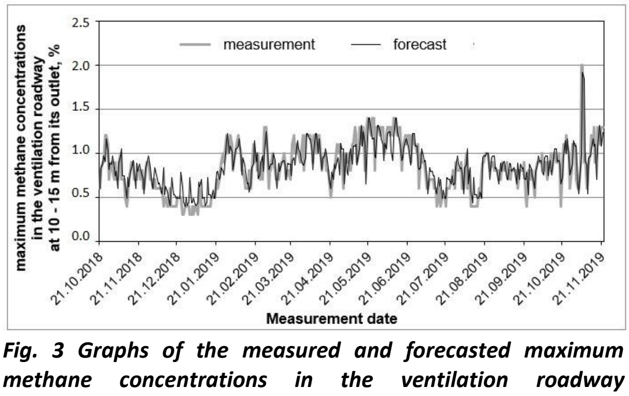

Fig. 3 Graphs of the measured and forecasted maximum methane concentrations in the ventilation roadway at a distance of 10-15 m from its outlet

Source: own study based on data from a mining company.

At the outlet of the ventilation roadway, the maximum concentration of methane only twice (on two consecutive days) reached a value not less than 2%. On the remaining days of the observation period, the values of the maximum concentration did not exceed 1.5%.

In 176 cases (out of 398) the measured values of methane concentration exceeded the predicted concentration values. On the other hand, the sum of the measurement concentration during the observation period of 335.80% CH_4 is lower than the sum of the forecast concentration of 340.56% CH_4. It follows from the above that most of the forecasts were made with a slight excess.

The correlation coefficient between the measured and forecast methane concentration is 0.81.

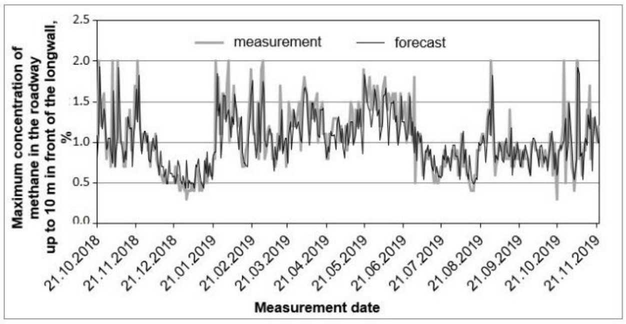

Fig. 4 Graphs of the measured and forecasted maximum methane concentrations in the ventilation roadway at a distance of up to 10 m from the longwall

Source: own study based on data from a mining company.

In the ventilation roadway, up to 10 m in front of the longwall, the maximum concentration of methane in 11 cases reached a value not less than 2%.

In 213 cases (out of 398) the measured values of methane concentration exceeded the predicted concentration values. The sum of the measured concentration during the observation period, amounting to 415.80% CH_4, is higher than the sum of the predicted concentration of 402.17% CH_4. It follows from the above that most of the forecasts were made with a slight underflow.

The correlation coefficient between the measured and forecast methane concentration is 0.70.

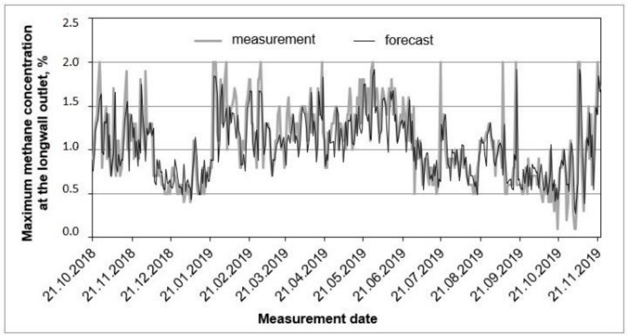

Fig. 5 Graphs of the measured and forecasted maximum methane concentrations at the outlet from the ventilation roadway

Source: own study based on data from a mining company.

At the longwall outlet, the maximum concentration of methane in 14 cases reached a value not less than 2%.

In 228 cases (out of 398) the measured values of methane concentration exceeded the predicted concentration. The sum of the measured concentration during the observation period, amounting to 426.10% CH_4, is higher than the sum of the predicted concentration of 409.29% CH_4. It follows from the above that most of the forecasts were made with a certain underflow.
The correlation coefficient between the measured and forecast methane concentration is 0.71.

ANALYSIS OF THE MEASURED VALUES

Table 1 presents statistical data characterizing the maximum concentration of methane in the three places discussed.

Table 1
Statistical parameters of the max. methane concentration

Statistical parameters of the maximum methane concentration	Roadway outlet		In the roadway, up to 10 m in front of the face of the longwall		Longwall outlet	
	M	F	M	F	M	F
average, % CH_4	0.84	0.86	1.04	1.00	1.07	1.03
median, % CH_4	0.8	0.9	1.0	1.0	1.1	1.0
percentile 0.75, % CH_4	1.0	1.0	1.3	1.2	1.4	1.3
percentile 0.90, % CH_4	1.2	1.2	1.6	1.4	1.7	1.5
minimum, % CH_4	0.3	0.4	0.3	0.4	0.1	0.3
maximum, % CH_4	2.0	1.9	2.0	1.9	2.0	1.9
range, % CH_4	1.7	1.5	1.7	1.5	1.9	1.6
standard deviation, % CH_4	0.30	0.28	0.39	0.32	0.43	0.34
coefficient of variation	33.04	26.8	37.49	31.26	40.02	33.09

M – Measurement, *F* – Forecast.

The data contained in Table 1 show that the highest average of the maximum measured methane concentrations occurred at the longwall outlet and amounted to 1.07% CH_4. In the roadway, up to 10 m in front of the face of the longwall, the average value of the maximum methane concentration was 1.04% CH_4, and at the outlet from the ventilation roadway – 0.84% CH_4, and thus it was the lowest.
The median values show that on 50% of the days of the measurement period, the maximum methane concentration at the longwall outlet did not exceed 1.1% CH_4, at a distance of 10 m in front of the longwall it did not exceed 1% CH4, and at the outlet from the ventilation roadway it did not exceed 0.84% CH_4.
On 75% of the measurement days (299 days) at the longwall outlet, the maximum methane concentration did not exceed 1.4% CH_4, at a distance of 10 m in front of the longwall it did not exceed 1.3% CH_4, and at the outlet from the ventilation roadway it was not higher than 1.0% CH_4.
On 90% of the measurement days (359 days), the maximum concentration of methane in the longwall did not exceed 1.7% CH_4, in the ventilation roadway at a distance of 10 m in front of the longwall it was not higher than 1.6% CH_4, and in the roadway at a distance of 10-15 m before outlet - not more than 1.2% CH_4.
The minimum maximum concentration in the longwall was 0.1% CH_4, in the ventilation roadway at a distance of up to 10 m from the longwall and at the outlet of this roadway it was 0.3% CH_4. However, the maximum concentration of methane in all the above-mentioned places was not less than 2%. Thus, the maximum concentration ranges were 1.9% CH_4, 1.7% CH_4 and 1.7% CH_4, respectively.
The largest dispersion of the maximum methane concentration measured by standard deviation was 0.43% CH_4 at the longwall outlet, 0.39% CH_4 up to 10 m in front of the longwall and 0.28% CH_4 at a distance of 10-15m before the outlet from the ventilation roadway.
The calculated values of the coefficients of variation were respectively (starting from the face outlet) 40.02%, 37.49% and 33.04%.
Taking into account the standard deviations and coefficients of variation, it can be concluded that the methane concentration at the longwall outlet was characterized by the greatest variability, and the lowest – at the exit from the ventilation roadway. All volatility values are within the average volatility range.

FORECAST VALUES ANALYSIS

The data contained in Table 1 show that the highest average of the maximum predicted methane concentrations occurred at the longwall outlet and amounted to 1.03% CH_4. In the ventilation roadway, up to 10 m before the outlet from the longwall, the average value of the maximum methane concentration was 1.00% CH_4, and at the outlet from the ventilation roadway – 0.86% CH_4, and thus it was the lowest.
The comparison with the measured values shows that at the outlet from the roadway the average predicted value is higher than the measured value. On the other hand, in the roadway up to 10 m in front of the longwall face and at the longwall outlet, the projected average values of the maximum methane concentration are lower than the measured ones by 0.04% CH_4.
The forecasted value of the median at the outlet from the roadway is 0.1% higher than the measurement and amounts to 0.9% CH_4. At a distance of up to 10 m in front of the longwall, the median is forecast equal to the measurement (1.0% CH_4), and at the longwall outlet the median is forecast 0.1% CH_4 lower than the measurement (1.0% CH_4).
The 0.75 percentiles of the forecasted and measured at the outlet of the roadway are equal to 1.0% CH_4. On the other hand, in the roadway up to 10 m in front of the face of the longwall and at the outlet of the longwall, the projected values are lower by 0.1% CH_4 than the measured ones and amount to 1.2% CH_4 and 1.3% CH_4, respectively.
Similarly, the 0.90 percentiles at the outlet from the roadway are 1.2% CH_4, up to 10 m in front of the longwall and at the longwall outlet are lower than the measurements by 0.2% CH_4 (1.4% CH_4 and 1.5% CH_4 respectively).
The forecasted minimum values of the maximum methane concentration are 0.1% CH_4 higher at the outlet from the roadway and at a distance of up to 10 m in front

of the longwall and amount to 0.4% CH_4, while at the outlet from the longwall the forecast value (0.3% CH_4) is 0.2% CH_4 higher than measured.

The forecasted standard deviations in each analyzed location are lower than the measured ones. At the outlet from the roadway, it is 26.80% CH_4 (lower by 0.02% CH_4), up to 10 m in front of the longwall 0.32% CH4 (lower by 0.07% CH_4), and at the outlet from the longwall it is 0.34% CH_4 (lower by 0.09% CH_4).

The coefficients of variation in each case are lower for the forecasted values. They are 26.8% (33.04% for measurements) at the outlet from the roadway, 31.26% (37.49% for measurements) and 33.09% (40.02% for measurements).

Both standard deviations and coefficients of variation indicate smaller fluctuations of the forecasted concentration in comparison to the measured concentration of methane.

SUMMARY AND CONCLUSION

The analyses of the maximum methane concentration in one of the longwalls presented above lead to the following statements and conclusions:

1. Due to the possibility of exceeding the permissible methane concentration in the ventilation air, and thus the occurrence of a break in coal mining, the forecast of the maximum methane concentration is more important than the forecast of the average methane concentration.
2. The total time of occurrence of the maximum concentration on a given day depends on methane content, intensity of exploitation and day of the week. This time ranges from a few seconds to a full twenty-four hours.
3. The fluctuation range of methane concentration at the outlet from the roadway and at a distance of up to 10 m in front of the longwall ranged from 0.3% CH_4 to 2% CH_4, and at the outlet from the longwall – from 0.1% CH_4 to 2% CH_4. The times of occurrence of the maximum methane concentration of 2% CH_4 and higher are assigned to the value of 2% CH_4.
4. The highest average value of the maximum methane concentration was found at the longwall outlet (1.07% CH_4). This parameter was 0.03% CH_4 lower in the roadway up to 10 m in front of the longwall, and 0.23% CH_4 lower at the outlet from the roadway. The forecast of this parameter at the outlet from the roadway was 0.02% CH_4 higher, while in the wall and in the roadway at a distance of 10 m in front of the longwall it was 0.04% CH_4 lower.
5. In all measurement sites, the maximum concentration of methane was not less than 2% CH_4, while the forecasts showed a concentration of 1.9% as the highest in each measurement site.
6. The fluctuation range of the maximum measurement concentration at the measurement points in the roadway was 1.7% CH_4, and at the longwall outlet 1.9% CH_4. However, the forecasted values in these places are lower and amount to 1.5% CH_4 in the roadway and 1.6% CH_4 in the longwall.
7. Measurement standard deviations in each of the measurement locations are higher than the forecasted values of these parameters. The same statement applies to the coefficient of variation. This proves that the maximum variability of the measured concentrations is greater than the forecasted concentrations.
8. The correlation coefficients between the measured and forecast values of the maximum methane concentration are 0.81 at the outlet of the ventilation roadway, 0.70 in the roadway at a distance of up to 10 m in front of the longwall and 0.71 at the outlet from the longwall. The assessment of compliance of the forecast with the measurements, determined on the basis of the determination coefficient, is 66% at the outlet from the roadway, 49% at a distance of up to 10 m in front of the longwall and 50% at the outlet from the longwall.
9. The authors of the article suggest carrying out more studies of the variability of the maximum concentration at the face outlet and up to 10 m in front of the longwall, and on this basis to create appropriate forecasting equations.

The conclusions of the article are of practical importance for the mining industry, where the control of methane concentration is crucial for the safety of employees and for maintaining the continuity of coal mining. It also seems reasonable to state that precise forecasting of the maximum methane concentration would allow for early reaction and taking appropriate preventive measures in the event of exceeding the limit values. It is therefore necessary to conduct practical research and implement proven methods to ensure the safety of hard coal exploitation, and thus to improve its efficiency.

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