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METHANE CONCENTRATION MEASUREMENTS IN THE LONGWALL AREA AS A DATA SOURCE FOR THE ASSESSMENT OF METHANE HAZARD

This article discusses the challenges of coal mine safety, particularly methane hazards, in the context of decreasing workforce and the need for more autonomous solutions. As hard coal production faces a phase-out due to international energy policies, the mining industry struggles with retaining skilled workers. The Sectional Methane Hazard Detection System (SDZM) is proposed as an autonomous solution to detect methane hazards by measuring methane concentrations along underground workings. The system operates using a series of algorithms that analyze the concentration data and identify hazard zones without the need for highly qualified personnel.

The SDZM method involves collecting methane concentration data from different sections of the mining operation and comparing them to reference profiles to assess potential hazards. A study conducted in the 841A longwall area of KWK B mine used simulations to assess methane distribution, which was then used to test the SDZM system's algorithms. The results show that the system can accurately detect high methane hazard levels, with sensitivity varying depending on the parameters set, such as the tolerance field for methane concentration changes.

The study concluded that the SDZM system is effective in detecting methane hazards, requiring minimal additional skills from workers. The system's performance can be enhanced by adjusting parameters like the methane concentration tolerance field, though excessively narrow tolerances could lead to false positives. Overall, the SDZM provides a valuable tool for enhancing safety in mines by autonomously identifying high-risk areas related to methane emissions.

Keywords: Methane concentration measurements; sectional measurements; experiment; individual methanometer; methane hazard assessment; detection of methane emission sources

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1. Introduction

International policy on fossil fuels leads societies to recognize the inevitable phase-out of hard coal production for energy purposes [1]. This brings a series of consequences, particularly significant economic burdens on the facilities, but also problems with maintaining highly skilled staff and hiring new employees who want to tie their future to work in the extraction plant [2,3]. Training employees and gaining experience is an important process from the perspective of work safety, which is also expressed in the ability to recognize hazards, for example through accurate and reliable measurements. Numerous changes in mine ventilation networks and the extraction of hard-to-reach coal resources bring additional risks [4]. These risks can be partially minimized through the intensification of safety controls and preventive measures concerning natural hazards. One of the natural hazards is the methane hazard, the prevention of which involves the proper regulation of the mine's ventilation network and frequent monitoring of methane concentration in the ventilation air, as well as an efficient methane drainage system [5,6]. Maintaining a high level of safety, with decreasing employment in the mining industry, leads to proposing new solutions that do not require highly qualified personnel and operate largely autonomously.

A proposed new solution is the Sectional Methane Hazard Detection System (System Odcinkowej Detekcji Zagrożenia Metanowego – SDZM) [7]. This system is designed for the prevention and identification of methane hazards in the context of measuring methane concentration along underground workings. It allows for the measurement of concentrations in workings by dividing them into measurement sections. The system continuously compares the methane concentration measurements collected from individual sections and assesses the hazard.

2. SDZM method and algorithms

The method of sectional methane concentration measurement is based on a series of methane concentration measurements. Each recording is a time series of methane concentrations obtained while the measurer moves along the working. The set of recordings is obtained through repeated passes by individuals along the same section. The sectional methane concentration measurement method is implemented in an individual methane detector through a series of algorithms. These algorithms were discussed in detail in the thesis [7]:

- Sectional Pattern Selection Algorithm – This algorithm is responsible for selecting the sectional patterns based on methane concentration measurements obtained while the measurer moves along the working. It helps in identifying the reference data for further analysis.
- Determination of Permissible Sectional Concentrations Area Algorithm – This algorithm determines the permissible range of methane concentrations within each section based on the recorded data. It helps in establishing safe concentration levels within the working environment. The result of the algorithm's work is the tolerance field envelope outlined around the group of segmental data.
- Data Classification Algorithm – The data classification algorithm categorizes the methane concentration data as low/high hazard. Low when data no exceed tolerance fiels, high if it exceeds tolerance field.
- Data Exchange Algorithm – The data exchange algorithm facilitates the exchange of measurement data between other methanometers, enabling the sharing of information related to methane concentrations and hazard detection.

These algorithms work together to analyze the methane concentration profiles recorded in sections as personnel move along the paths. By normalizing, comparing, and evaluating the data against tolerance fields derived from reference sections. During personnel movement along these sections, the device measures the methane concentration and records it as data sequences in its memory. The algorithm compares normalized sections searching for anomalies by determining the field of tolerance for changes in methane concentration for the entire group of segments. The key role in detecting anomalies in profiles is played by the reference section selected as the most representative one from the entire group of profiles stored in the device's memory. The choice of the reference sections is crucial in classifying the new sectional data, hence a rule for selecting the reference section has been established and described in the work [7]. The new measurement data is evaluated against the tolerance field of methane concentration changes derived from the reference section. If the new section data falls within the tolerance field, it is considered that there are no significant methane concentration changes indicating a hazard.

The algorithms enable the detection of methane accumulation or increased methane emissions along the paths or in other areas where the crew is present [8,9].

3. Hazard level analysis at the longwall outlet based on crew movement simulation

The analysis focused on the 841A longwall area at KWK B, which was ventilated using a "U" system with additional ventilation provided to the wall outlet. This longwall area was part of a research experiment detailed in work [10], allowing for the identification of methane sources in the longwall area and the determination of air flow parameters and methane distribution along the longwall during cutting with a shearer through "in situ" measurements. The issue of developing a model for methane emission from the longwall face before and behind the shearer was presented in work [11]. The developed mathematical model was modified in subsequent works [12,13], enabling validation studies of the model using numerical simulations of the longwall shearer operation, the longwall conveyor, and the transport of the extracted material [14].

Methane concentration and air velocity profiles recorded by the mine monitoring system were compared with profiles obtained from computer simulations. This comparison demonstrated that it is possible to reproduce temporal profiles of air velocity and methane concentrations in the longwall area. This indicates that many of the adopted models and algorithms are correct [14-16].

As an example of airflow and methane flow simulations in the 841A longwall area and the area of the decommissioned 841B wall, as well as their abandoned working areas under the conditions of longwall cutting with a shearer, a database containing the parameters of the applied mathematical model was used. This database was supplemented with parameters of the shearer speed control algorithm [14]. The developed numerical model of the longwall area is shown in Fig. 1. Longwall 841A, exploited using the longwall system, was ventilated in a "U" pattern along the coal face. The wall had a length of 130 meters, an average height of 2.9 meters, and a face advance of 550 meters. The methane hazard category was IV. The transport of the extracted material was carried out by a conveyor belt with a speed of up to 2.0 m/s. The 841A longwall area in seam 405/2 was characterized by an absolute methane emission of 18.1 m^3 CH_4/min. The average methane drainage efficiency assumed in the technical project for wall exploitation was 35%. The amount of air at the inlet to the wall was 1115 m^3/min. The outlet from the longwall was

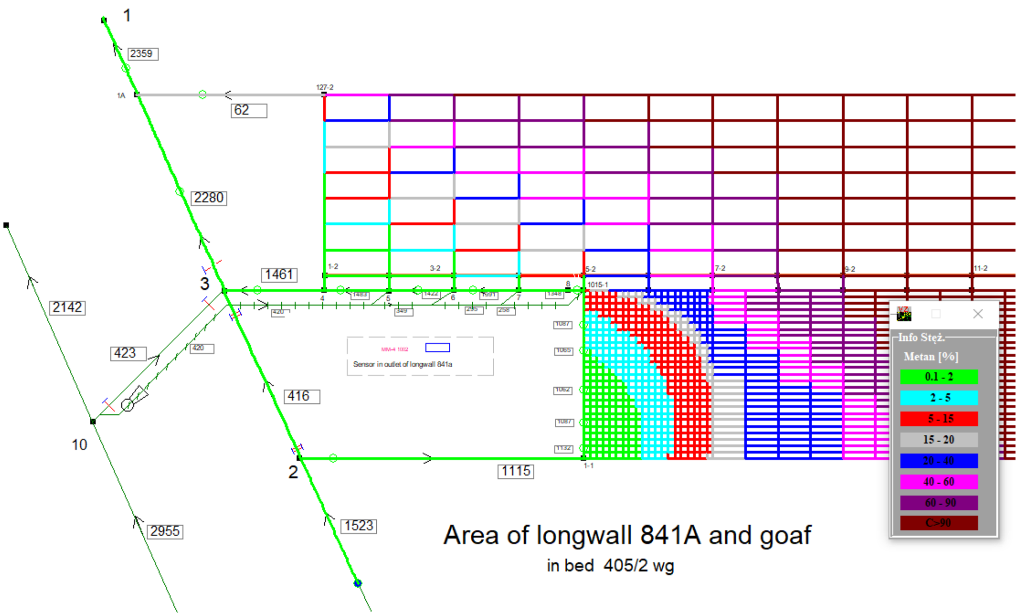

Fig. 1. Spatial diagram of the longwall 841A area – numerical model

refreshed (263.5 m^3/min) using a duct that delivered fresh air to the decommissioned section behind the longwall. The total airflow at the outlet of the ventilation roadway was 1461 m^3/min. Along the upper wall roadway, connections with the abandoned working areas of the decommissioned adjacent longwall 841B were included, in the form of segments placed every 5 meters. Therefore, methane emissions from the longwall, the extracted material, and the abandoned working areas of both longwalls were considered. In the lower longwall roadway, methane emissions from the transported material on the conveyor belt were also taken into account.

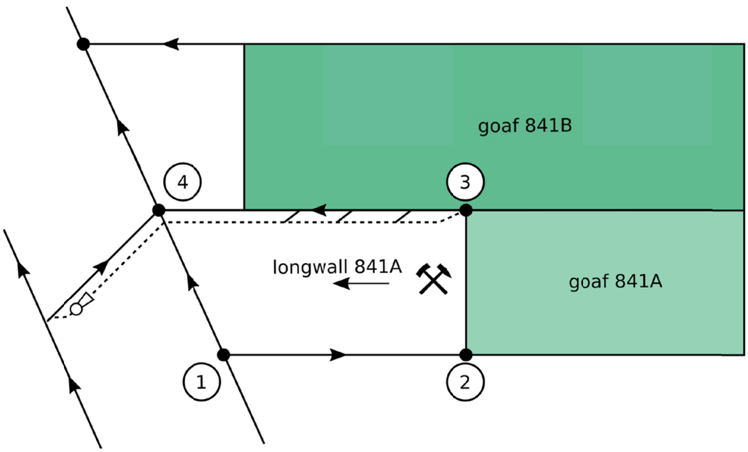

Fig. 2. Ventilation diagram of the 841A KWK B longwall area

The developed numerical model allowed for the determination of the methane concentration distribution in the ventilation pathways of the area, which formed the basis for further research aimed at obtaining a data source for inferring methane hazards based on the operation of individual methane detectors working according to the algorithms of the Methane Hazard Detection System. Fig. 2 shows the working ventilation schematic useful for further research.

The route taken by the miners included the upper longwall roadway and the last section at the longwall outlet, which is marked in green in Fig. 3.

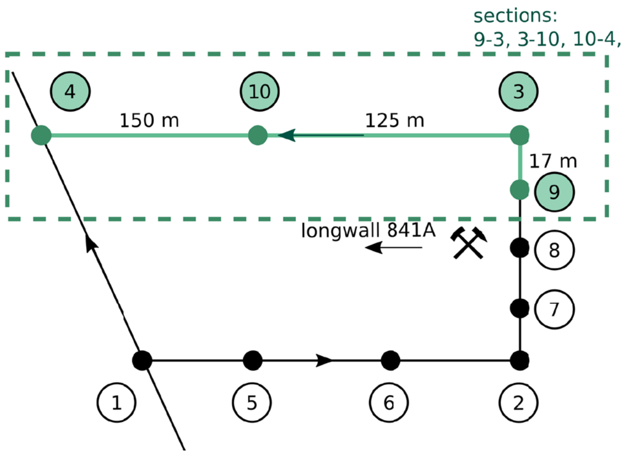

Fig. 3. Distribution of additional nodes (WRP, marked in green) for longwall 841A

The route included nodes 9 to 4 according to the diagram (Fig. 3). The total length of the route was 584 meters, including both directions. The route was assigned to four miners, each given equal traveling speeds but different starting positions (TABLE 1).

The route recorded as a node list is as follows: 9, 3, 10, 4, 10, 3, 9. Node number 9 serves as both the start and end of the route.

TABLE 1

Initial positions of miners

Miner's identification number	Relative initial position [m/m]	Absolute initial position [m]
G1	0	0
G2	0.1	58
G3	0.5	292
G4	0.6	350

The initial positions of the miners and the directions of movement are plotted on the diagram below (Fig. 4).

The miners moved cyclically along a preset route. The flow conditions and methane concentrations at each point of the route varied according to the Ventgraph program simulation.

The miners' travel time was 6 hours and 26 minutes.

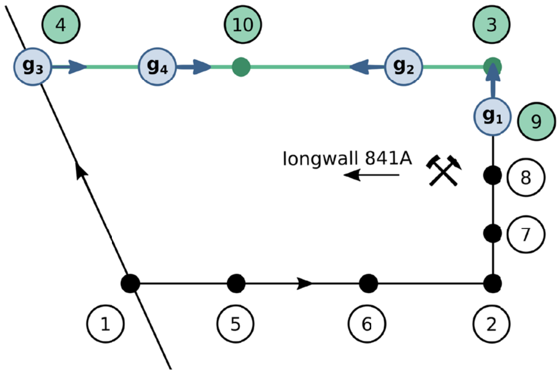

Fig. 4. Distribution of additional nodes (WRP) for longwall 841A

The analysis adopted parameters for the methane concentration tolerance field:

$$\begin{cases} vdMax = 0,2 \text{ m/s} \\ dch4 = 0,1\ \% \end{cases} \tag{1}$$

The search for the reference profile for methane hazard assessment was based on the last 30 sectional data. The simulation parameters adopted allowed for effective detection of high-level hazards.

4. Results

The sectional data stored in the miners' devices mostly overlap; differences only concern the last recorded data, which the devices did not manage to transmit before the end of the simulation. Within one route traversal, there were 8 data exchanges. In general, the number of data exchanges can be expressed by the formula:

$$L_{wym} = N_p \cdot k_p \cdot \binom{N_u}{N_{uwi}} \tag{2}$$

where: L_{wym} – number of data exchanges, N_p – number of route traversals, k_p equals 1 when the route traversal occurs only in one direction, k_p equals 2 when the route traversal occurs in both directions, N_{uwi} – number of devices with which direct information exchange can occur.

For a single route traversal, in the analyzed case, we obtain:

$$L_{wym} = N_p \cdot k_p \cdot \binom{N_u}{N_{uwi}} = 1 \cdot 2 \cdot \binom{4}{3} = 2 \cdot \frac{4!}{3!(4-3)!} = 8 \tag{3}$$

Below are the results of hazard assessment by one of the devices (miner device No. G1), noting that the results of the other devices do not significantly differ. Depending on the section assessed for hazard, the results varied – the closer to the longwall, the more often the devices indicated a high level of hazard.

In the figure (Fig. 5), the black line represents data from a virtual sensor placed at the 75th meter of section 4-10, which is halfway along the length of the section. Onto this line, points corresponding to the hazard level were plotted, with the hazard assessment ending at the time corresponding to the position of this point on the time axis. A high hazard level is indicated by red color in 4 groups of sectional records, each occurring near a local maximum. In total, a high hazard level was observed in 20 cases.

In the figure (Fig. 6), similar to the previous one, the hazard level assessment is overlaid on the methane concentration profile for a selected point on the section. In this case, it was a point on section 3-10, located 62 meters from node number 3. A high hazard level was observed in 16 cases.

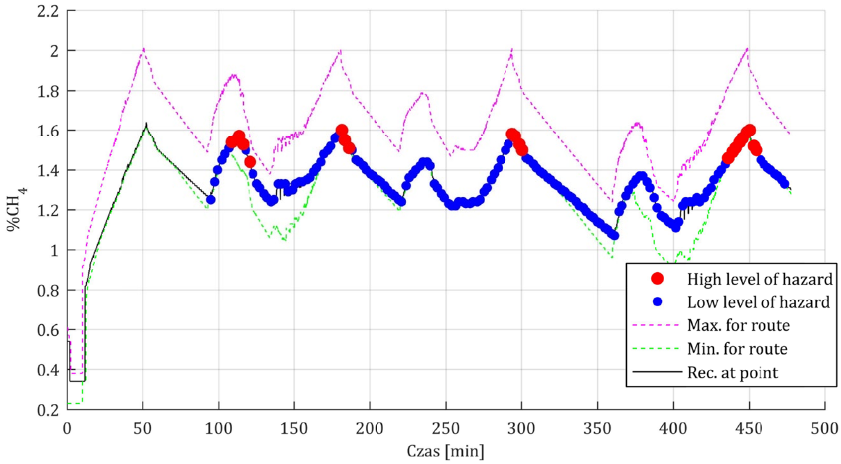

Fig. 5. Hazard assessment result for miner 1 in terms of point measurement and methane concentration change range from section 4 to 10

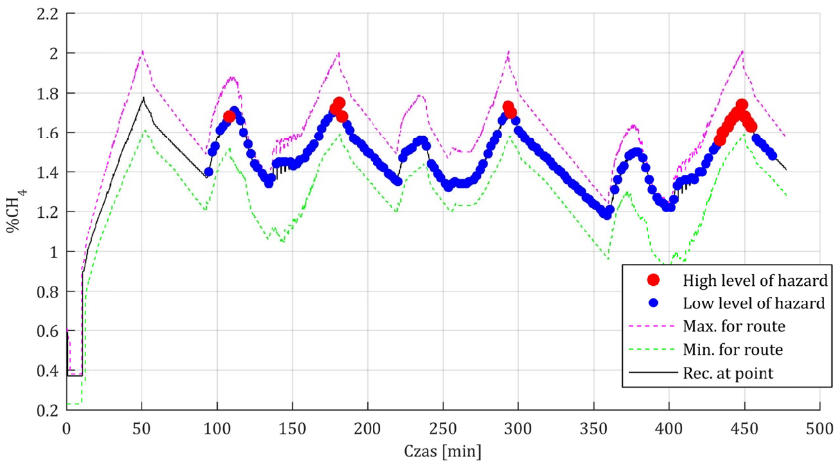

Fig. 6. Hazard assessment result for miner 1 in terms of point measurement and methane concentration change range from section 3 to 10

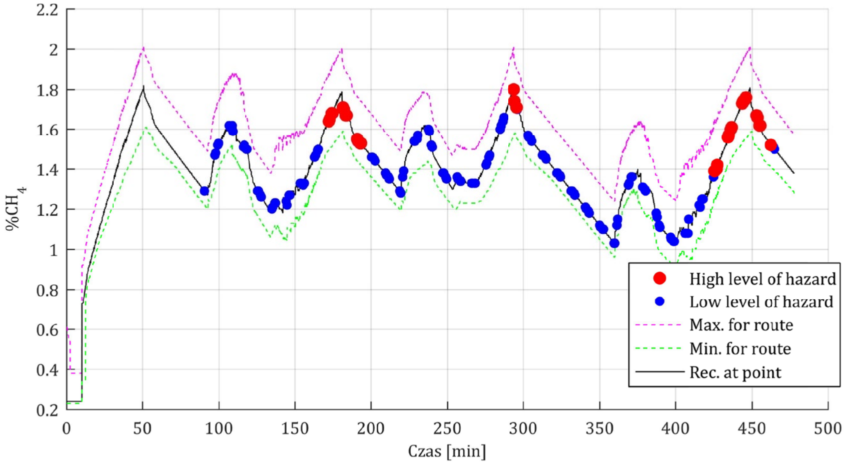

Fig. 7. Hazard assessment result for miner 1 in terms of point measurement and methane concentration change range from section 9 to 3

In the figure (Fig. 7), similar to the previous ones, the hazard level assessment is overlaid on the methane concentration profile for a selected point on the section. In this case, it was a point on section 9-3, located 8 meters from node number 9. A high hazard level was observed in 31 cases. Next, a sensitivity analysis of hazard detectability was conducted based on two factors: the value of the dch4 parameter and the number of historical data points considered by the algorithms. The dch4 coefficient, related to the tolerance field width and the accuracy of the methane detectors, was set at 0.2% in the first case and 0.1% in the second case. The number of sectional data points considered in determining the sectional pattern was also varied – in each case, 10, 30, and 50 sectional data points for each section were considered. The results are presented in TABLE 2.

TABLE 2

Number of sectional records with high hazard level detected

Section	Tolerance to changes in methane concentration: $d_{ch4} = 0.2\%$			Tolerance to changes in methane concentration: $d_{ch4} = 0.1\%$		
	10 sections back	30 sections back	50 sections back	10 sections back	30 sections back	50 sections back
9-3	16	31	34	45	60	57
3-10	8	16	17	55	63	59
10-4	6	20	16	52	56	54

TABLE 2 contains the results of further calculations for different parameters of the hazard detection algorithm operation. The hazard assessment was conducted for methane concentration tolerance fields (d_{ch4}) of 0.2% and 0.1%. A higher concentration tolerance resulted in decreased hazard detectability, which was an expected outcome. It was noted that for the narrower methane concentration tolerance field, the hazard detectability remained at a similar level for the three cases examined: 10, 30, and 50 sections back. This indicates that the sectional pattern was similar to many others remaining in memory, meaning the change in the sectional pattern did not significantly affect the hazard assessment, which is a positive result. For the wider tolerance field (d_{ch4} = 0.2%), the results for the detectability of high hazard levels for the smallest number of sections (10 sections back) stood out clearly, indicating significantly fewer sections with high hazard levels than in the other cases.

5. Conclusions

The methane hazard detection algorithms were tested using simulated methane concentration distribution data along the ventilation paths in a selected coal mine. These simulation results were validated against real-world measurement data from the mine's gasometry system, demonstrating that the models and algorithms used are robust. The simulations allowed for a deeper understanding of how the algorithms perform under real mine conditions, particularly in terms of the minimum amount of data needed for accurate hazard detection. It was determined that a minimum of 30 data records per section is required to make a reliable hazard assessment.

The results of the sensitivity analysis indicate that narrowing the tolerance field by adjusting the d_{ch4} parameter increases the sensitivity of the algorithms, leading to a higher number of detected high methane hazard levels. However, excessively reducing the tolerance may cause false positives, where the system detects a hazard even when the actual methane concentration is low. This suggests that while the system's sensitivity can be fine-tuned, it must be balanced to avoid over-detection and unnecessary alarms.

Importantly, the Sectional Methane Hazard Detection System (SDZM) has shown that it can operate effectively without requiring significant new skills from mine personnel. The system's autonomous nature and reliance on existing infrastructure, such as methane detectors and ventilation systems, make it an ideal tool for improving safety in mining operations with decreasing workforce sizes. By automating the detection of methane hazards, the system not only enhances operational safety but also reduces the dependency on highly trained personnel, making it a viable solution in the face of challenges related to workforce retention in the mining industry.

The implementation of the SDZM system has the potential to significantly improve hazard detection capabilities, identify dangerous zones more efficiently, and contribute to better overall safety management in mining operations. Future research could explore further optimizations in algorithm performance and the integration of additional sensor data to enhance the system's accuracy and responsiveness.

The authors declare that they have no conflict of interest.

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