Article

The Impact of Cutting with a Shearer on the Conditions of Longwall Ventilation

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Abstract: In coal mines that are exploiting methane-saturated seams, high-level emission of methane is often the basic limitation for modern and high-efficiency longwall complexes. This paper presents selected observations and tests carried out in the Cw-4 longwall in seam 364/2 of the Budryk mine, which belongs to JSW SA. To observe the methane levels in the Cw-4 longwall, additional sensors were installed at the end section of the longwall from the side of the gobs, and the air velocity and methane concentration were registered in a multi-point system that were built in the selected longwall cross-section. The air parameters were recorded in the monitoring system. The use of multi-point simultaneous measurements of the local velocities and concentrations of methane in the longwall cross-section allowed for the precise determination of the air and methane volume flow using the velocity field method. This allowed us to perform a comparative analysis of the obtained records of the air parameters using special software to determine the distribution of the parameters in the cross-section of the excavation. An important element of the study was the simultaneous registration of the methane concentration in the longwall, information on the operating times, the direction of shearer operation, and the type of work being done (i.e., mining/cleaning).

Keywords: monitoring of methane concentration; ventilation of mines; measurements of ventilation parameters

1. Introduction

Methane hazard is an important factor when mining coal seams that are saturated with methane [1]. Research conducted in the Polish and international mining sectors indicates that methane hazard not only influences the safety of longwall operations but also imposes limitations on output as the operational continuity of longwall complexes is disturbed [2,3]. In very gaseous mines, methane is often the main limitation for the functioning of modern and highly efficient longwall complexes [3,4]. In current mining operations, significant efforts are being made to automate longwall complexes, which takes into account safety conditions [4–6]. The methods currently being developed for automatic data processing and analysis using “data mining”, among others, support the identification of the influence of coal mining on ventilation conditions, particularly in gaseous mines where methane is present [7–9].

Studies on the influence of shearer mining on ventilation conditions in a longwall complex and the development of air velocity and methane concentration transient states were conducted in Poland in the Budryk [10] and Bielszowice [11] coal mines. These studies revealed considerable disturbances in the air parameters in the longwall workings during shearer operation. These resulted from the large dimensions of the shearer, which when operating in the longwall, is a movable obstacle that narrows the cross-section of the longwall drift, increases the mixing of air with methane, and intensi-
fies the inflow of methane from gobs. The observations [12], which were measurement experiments carried out over a few hours, along with periodic in situ experiments, confirmed the existence of a strong relationship between the disturbances of the air parameters in the longwall complex and the direction of the shearer operation in relation to airflow direction.

Longwall Cw-4 in seam 364/2 in the Budryk mine was selected as the site for observations and studies. In this study, aside from the traditionally used methane sensors that are included in the mine monitoring system, eight additional methane wireless sensors were used. These sensors were installed on powered support units (sections) in the end portion of the longwall between sections No. 5 and 75 (Figure 1) from the gob side. Moreover, in the longwall Cw-4 area, the air parameters were recorded over the course of the in situ experiments. The aim of these experiments was to determine the local methane concentrations along the longwall face using a scattered methane-anemometers system that was equipped with an increased number of sensors. In the experiments, which lasted a few hours each, a multi-point system was also used with methane-anemometers that were installed on a truss on selected cross-sections of longwall Cw-4 marked in red in Figure 1. A part of the recorded data was used in the study by Jamroz and Wasilewski [12]. Over the course of the long-term studies and numerous experiments [13], measuring data were obtained, which extended the knowledge concerning changes in the methane concentration and the volume of the methane stream in a longwall complex during shearer operation. The collected data allowed for the development of numeric models of the longwall area [14] and the identification of model parameters and model validation. These data took into account the methane inflow over the course of shearer operation cycles [15].

The main aim of the studies described in this paper was to conduct analyses of the methane concentration distribution and the methane volume stream in the cross-section of a longwall drift during cutting with a shearer. In situ experiments were performed with the use of a unique measuring apparatus in the form of a multi-point system with many methane-anemometers installed on selected cross-sections of the longwall. In this way, the air velocity and methane concentration were simultaneously recorded and using the developed IZO-VM software, the distribution of air velocity and methane concentration in the longwall cross-section was determined. As a result of the data recording, we had the opportunity to compare the methane concentration distribution in the longwall cross-section with point recording of the methane concentration along the longwall face in the extended monitoring system [12]. This was of particular interest as point measurements constitute the basic method of measuring the methane concentration in mines.

2. Description of the Object of Research—Longwall Cw-4, Seam 364/2

Longwall Cw-4, seam 364/2, had a length of up to 243 m and a digging height of 1.5 to 2.0 m. We installed and numbered 156 powered consecutive support sections, starting from gate Cw-4. The technical equipment in the longwall face consisted of a shearer (KSW-460 NE Famur, Katowice, Poland), an armored face conveyor (type, manufacture, city, state abbreviation, country) (AFC) (Rybnik 850, Famur, Katowice, Poland), a beam stage loader (type, manufacture, city, state abbreviation, country) (BSL) (PZP_Kobra 2, Famur, Katowice, Poland) with crusher, and belt conveyors as the haulage system.

2.1. Longwall Ventilation

Longwall Cw-4 in seam 364/2 was ventilated by means of a reversed “Y” type ventilation system (Figure 1), with a return air transport along the gobs to the return shaft V. Intake of air into longwall Cw-4 was along gate Cw-3. Return air from longwall Cw-4 was supplemented with air flowing along gate Cw-4.
2.2. Monitoring of Air Parameters for the Longwall Area

Longwall Cw-4 in seam 364/2 was protected in the monitoring system with an additional methanometer that was located in the middle of the longwall (Figure 1), in compliance with the mining safety regulations that were in place. Furthermore, the longwall area was provided with additional methane detectors (MB638-MB619, marked in blue) installed at the end segment of the longwall (Figure 1).

In Figure 1, at the end segment of the longwall face and between the powered roof support section No. 5 and No. 75, from the gob side, additional methane wireless sensors (MB638–MB619) were installed. The traditional methane sensors of the mine monitoring system registered the methane concentration in 5-s cycles, with a resolution of 0.1% CH₄, whereas the additional methane sensors (MB638-MB619) registered the methane concentration in 1-s cycles, with a resolution of 0.01% CH₄. Data from the extended system were recorded on a regular basis in the archives of the monitoring systems. Independent of the long-term observations in the drift of longwall Cw-4 and in the longwall area, a number of in situ measurement experiments were performed. The aim of these was to observe the methane concentration distribution in the longwall drift cross-section during cutting with a shearer [12]. For this purpose, the multi-point system for measuring the air velocity and methane concentration was used, in which the methane-anemometers that were located in the longwall drift cross-section, close to the 7th section of powered roof supports (Figure1., marked in red), recorded the local air velocities and methane concentrations. Additionally, for the purpose of this study, the records of the shearer and AFC operations in longwall Cw-4 in the respective monitoring systems and the records that indicated the working direction (up/down) with the type of operation (cutting/cleaning) were used. This enabled us to assess the influence of cutting and machinery use on the methane concentration distribution along the longwall face.

3. Testing in the Mine on 14 January 2014

Testing was performed in the form of in situ experiments on 14 January 2014 during the production shift between 7:00–12:00. During this time, in longwall Cw-4, the shearer executed three cutting cycles with an advance of 1.6 m (Figure 2). The shearer started from the bottom of the longwall face at 7:30 and reached the top at 8:00 in cleaning mode. Subsequently, between 8:00 and 9:00, it performed cutting from the top to the bottom. It then went up again in cleaning mode and went from the top to the bottom to support section 80, cutting until 11:35, at which point the shearer broke down.

During the experiment [12] in the longwall Cw-4 area, the air velocity and methane concentration were measured in 1-s cycles by the mine monitoring system. In parallel,
also in 1-s cycles, the methane concentration levels were registered by additional wireless methane sensors that were installed in the drift of longwall Cw-4 (Figure 1). In the multi-point system that was installed in the cross-section of the longwall drift, at the 7th powered support section (Figure 1), the methane concentration and air velocity were also recorded by means of methane-anemometers. Synchronous recording of the equipment operation time in longwall Cw-4 on 14 January 2014 between 7:00 and 12:00 revealed one long technical break in operation of longwall equipment, between 9:20 and 10:20, when operation of the shearer and conveyors was halted. Therefore, the analysis focused on the time before the interruption (i.e., from 7:40 to 9:20). During this time, in longwall Cw-4 the shearer executed more than three cycles (cleaning-cutting-cleaning), with an advance of 1.6 m (Figure 2).

![Figure 2. Shearer operations in longwall Cw-4 recorded by operation controller.](image)

3.1. Recording of the Air Velocity by the Monitoring System in the Longwall Cw-4 Area

The air velocity in the longwall Cw-4 area was recorded by the monitoring system (Figure 1). This comprised of three anemometers and two anemometers at the intake/inlet V369 and outlet V2349 outside the area, respectively. The recorded air velocities revealed significant fluctuations in the instantaneous values. Only after the application of signal smoothing using the moving average method were the air velocity curves made legible (Figure 3). Figure 3 provides the registered air velocities in the analyzed period (i.e., from 7:40 to 9:20).
3.2. Recording of the Methane Concentration in the Longwall Cw-4 Area Using the Monitoring System

The methane concentration in the longwall Cw-4 area was tracked using eight methane sensors in the monitoring system, three of which were located in the longwall. The methane concentrations that were recorded in the system after smoothing show the nature of the changes in the concentration at various points of the longwall area (Figure 4), together with the changes that were caused by the shearer operation in the longwall face. Figure 4 also provides the recorded methane concentrations in the analyzed period (i.e., from 7:40 to 9:20 on 14 January 2014).

Figure 3. Smoothed air velocity data curves for the longwall Cw-4 area on 14 January 2014.

Figure 4. Smoothed methane concentration data for the longwall Cw-4 area.

3.3. Recording of the Methane Concentration by the Wireless System in Longwall Cw-4

The shearer operation and standstill cycles significantly influenced the changes in the methane concentration that was registered in the monitoring system by the additional wireless methane sensors (MB638-MB619) in the longwall end segment between 7:00 and 9:00. It can be seen (Figure 5) that in the first part of the period, the additional methane sensors registered a steady increase in the methane concentration, up to a value of over 1.4% CH₄, with the highest concentrations measured by the methane sensor MB638 (which was installed close to the middle of the longwall face near powered support section 35). Uniform fluctuations in the methane concentration values that were measured by all of the additional methane sensors were also noted. Changes in the methane concentration that were recorded by the methane sensors (MB638- MB619) installed in the drift of the longwall were correlated with the changes in shearer operation direction and the change in operation from cutting to cleaning (Figure 5).
3.4. Recording of the Air Parameters by the Multi-point System in the Cross-Section of Longwall Cw-4

In situ experiments were conducted in the longwall Cw-4 [12] to follow the distribution of methane concentrations in the longwall drift cross-section during cutting with a shearer. A multi-point measurement system was used for measuring methane distribution in these experiments with methane-anemometers located in the cross-section of the longwall drift near the powered roof support section 7 (Figure 6). This was performed by recording the local air velocities and the methane concentration directly onto the stored memory of these measuring devices.

Figure 6. Location of additional sensors and the multi-point system in longwall Cw-4.

The recorded air velocities measured by the multi-point system in the cross-section of longwall Cw-4, recorded locally by the methane-anemometers near the powered roof support section, are shown in Figure 7. As a result of substantial fluctuations in the instantaneous values that were registered by the methane-anemometers in 1-s cycles, the curves were smoothed by applying the moving average method. Slight changes in the air velocity can be seen during shearer operation, as registered locally by the anemometers in the cross-section where they were installed.
Figure 7. Smoothed air velocity curves from the multi-point system in longwall Cw-4.

Figure 8 shows the recorded methane concentrations that were obtained using the multi-point system in the cross-section of longwall Cw-4. These were measured locally by methane-anemometers that were near the powered roof support section 7 in relation to equipment operation, measured from 7:40 to 9:00.

Two shearer operation cycles can be clearly distinguished (mining-cutting/cleaning). Fluctuations in the instantaneous methane concentration values that were recorded in the cross-section using the multi-point system revealed an upward tendency in the cutting
(mining) cycles. The cyclic nature of the changes in the methane concentration was also noted for the cleaning mode, as the shearer, when going up, moved away from the installed methane-anemometers, whereas in cutting mode, the shearer travelled down, approaching the installed methane-anemometers. Furthermore, significant differences in the recorded methane concentration values were noted in the longwall cross-section, as the values reached 0.8% CH₄ in the cutting mode and approximately 0.4% CH₄ in the cleaning cycles. This fact also confirms the importance of the location of methane sensor installation to ensure the reliable assessment of methane that is released depending on shearer operation mode. This is also important for the prevention of methane threats in the longwall complex.

A comparison was also made between the methane concentration that was recorded using methane sensors that were located along the longwall face in the wireless system (Figure 2) and local recordings of the methane concentration in the longwall cross-section using methane-anemometers in the multi-point system that were installed close to section 7 of the powered roof supports (Figure 7).

The comparison of the methane concentrations recorded using both measurement systems is presented in Figure 9.

![Figure 9. Comparison of the recorded methane concentrations using the wireless sensors and the multi-point system in longwall Cw-4 between 7:40 and 9:00, in relation to equipment operation.](image)

The methane concentration values that were recorded along the longwall face (MB638-MB619) (marked in blue) and the values that were recorded in the longwall cross-section by the multi-point system (the red lines) have a similar curved shape and correctly reflect the changes in the methane concentration that resulted from the functioning of the mining equipment; however, the methane concentration values that were recorded in the cross-section were higher than those that were recorded along the longwall face.

Additionally, Figure 9 contains a black line which reflects the averaged methane concentration of the values that were recorded by the methane-anemometers, constituting the multi-point system in the longwall cross-section. This confirms the significant similarity between the methane concentration values that were recorded by the methane sensors that were installed along the longwall face and the average concentration in the cross-section.
It is also of interest to compare the methane concentration values that were recorded by the wireless sensor MB619 (section 5) that was located between the powered support sections (Figure 10, blue line), and the average methane concentration in the cross-section of longwall Cw-4 that was recorded by the multi-point system that was installed at section 7 (Figure 10, red line). This comparison addresses the issue of whether the methane concentration measurements that were made using the single sensor that was located between powered support sections reflected the actual changes in the average methane concentration in the air stream flowing through the longwall. On the basis of a comparison between the recorded values (Figure 10), it was possible to confirm the good compatibility of both.

Figure 10. Comparison of the recorded methane concentration for the wireless sensor MB619 (section 5) and the average methane concentration in the cross-section of longwall Cw-4, recorded by the multi-point system (section 7).

4. Determination of Air Flow Velocity and Methane Concentration in the Cw-4 Longwall Drift

One of the aims of the research that was conducted using the multi-point system (Figure 6) was to elucidate the nature of changes in the velocity field and the methane concentration through visualization of the longwall ventilation process. This was achieved by observing the changes in the flow velocity in the time-period for each anemometric sensor in the system. This showed the level of flow fluctuations in a given location. Momentary velocity fields are represented on the 2D charts as lines of equal velocity (isotachs) [16].

The authors' IZO-VM computer program [16] was used to enable the visualization of the air velocity and methane concentration distributions in the cross-section of the coal mine. The IZO-VM software enabled the calculation of the air volume and methane stream in the working (longwall) cross-section using the velocity field method [17]. In longwall Cw-4, in situ experiments were carried out [12] to examine the methane concentration distribution in the longwall drift cross-sections during mining using a shearer. In these studies, the aforementioned multi-point system (Figure 6) was used with the methane-anemometers in the longwall drift cross-section, close to section 7 of the powered roof supports to record the local air velocities (Figure 7) and methane concentrations (Figure 8).

Using the local air velocities and methane concentrations that were obtained with the multi-point system, the IZO-VM software was used to determine the air flow lines of
equal velocity (isotachs) (Figure 11) and the methane concentration isolines in the longwall cross-section (Figure 12).

**Figure 11.** Velocity profile in the Cw-4 longwall cross-section at 8:00.

The chart of the 2D velocity field (Figure 11) shows the evolved velocity profile, with the highest air velocity value being in the vicinity of methane-anemometer No. 1, 0.44 m from the mined solid coal and 1.28 m above the floor of longwall Cw-4.

Moreover, using the IZO-VM software, the surface area of the cross-section of the measurement site and the stream of flowing air and methane were determined. The obtained results are shown in Figures 12 and 13. The methane concentration isolines (Figure 12) indicated that the area with the highest methane concentration was the area where the coal has been previously cut (methane-anemometer No. 1), which suggests that most of the methane flowing into the longwall space during shearer operation came from the uncovered solid coal. With regard the velocity profile of the air and methane flowing mixture, as shown in Figure 11, and the methane concentration profile, as shown in Figure 12, the highest methane concentrations were noted in the area between the surface of the mined coal and the face conveyor (AFC), in the upper part of the cross-section.
Figure 12. Methane concentration profile in the Cw-4 longwall cross-section at 8:00.

Figure 13 shows a screenshot from the IZO-VM software, containing the changes in the air volume stream (blue line, upper graph) and changes in the methane volume stream (blue line, lower graph) between 7:40 and 8:50. The average stream of air was 6.46 m³/s (388 m³/min), while the average methane stream was 0.0706 m³ CH₄/s (4.23 m³ CH₄/min). The cross-section surface area was 6 m². The graphs indicate substantial fluctuations in the air flowing through the cross-section of longwall Cw-4. Similar flow characteristics can be noted in Figure 7, with marked differences in the momentary air velocity values.

Figure 13. Air and methane volume flow in longwall CW-4, section 7.
Figure 13 shows that from 8:10, an increase in the methane volume stream and methane concentration levels (Figure 8) were observed, which was the result of the shearer cutting operation in the longwall face. The observed methane velocity and the concentration that was measured using the methane-anemometer No. 1 (Figure 14) in the longwall CW-4 revealed a substantial variability in the flow velocity. The average air flow velocity that was recorded by methane-anemometer No. 1 was 1.74 m/s, while the average methane concentration was 1.30% CH₄.

![Graph of air velocity and methane concentration from measurements for a selected sensor](image)

**Figure 14.** Changes in the air velocity and methane concentration for sensor No 1. between 7:40 and 8:50.

Table 1 shows the average velocities and average methane concentrations between 7:40 and 8:50 for all methane-anemometers of the multi-point system that were located in the cross-section of the longwall drift close to the 7th section of the supports, as indicated in Figure 6. The x,y coordinate system for the sensor was located at the bottom, with 0m being close to the solid coal (Figures 11 and 12).

**Table 1.** Average air velocities and methane concentrations.

| Sensors | Location of Sensors | Velocity (m/s) | Methane (%) |
|---------|---------------------|---------------|-------------|
| No. 1   | X (m) 0.44, Y (m) 1.28 | V 1.74 | C 1.30 |
| No. 7   | X (m) 1.04, Y (m) 1.27 | V 1.33 | C 1.23 |
| No. 6   | X (m) 1.64, Y (m) 1.29 | V 1.20 | C 1.11 |
| No. 12  | X (m) 2.21, Y (m) 1.29 | V 1.18 | C 1.09 |
| No. 3   | X (m) 1.61, Y (m) 0.92 | V 1.54 | C 1.03 |
| No. 10  | X (m) 2.23, Y (m) 0.9  | V 1.39 | C 1.13 |
| No. 16  | X (m) 2.41, Y (m) 0.89 | V 1.36 | C 1.09 |
| No. 8   | X (m) 2.95, Y (m) 0.84 | V 1.24 | C 1.04 |
| No. 15  | X (m) 3.36, Y (m) 0.89 | V 0.85 | C 0.96 |
5. Discussion

Recording of the air parameters using a mine monitoring system and in situ experiments enabled us to extend our knowledge of methane distribution in a longwall drift during shearer operation. This research demonstrated that the sensors that were located behind the hydraulic supports in the area where the headboard of the powered supports connects with the shield structure correctly registered changes in the methane concentration that was caused by shearer operation in the longwall face.

An important element of this study was the simultaneous recording of the methane concentrations along the longwall face and the registering of the shearer and armored face conveyor (AFC) operation, including information concerning the working direction (up/down) and the working type (cutting/cleaning) in longwall Cw-4. From the perspective of the research conducted thus far, this study was unique and allowed for the analysis and assessment of the influence of longwall mining operations on the distribution of the methane concentration along the longwall face.

An important element of this research was recording of the air velocity distribution and methane concentration in the cross-section of the longwall. This was carried out during the in situ experiment with the use of a unique measuring apparatus as a multi-point system, with methane-anemometers distributed in the cross-sectional area of the excavation. This research has demonstrated that the methane concentrations that were recorded along the longwall face properly reflected the changes in the methane concentration in the seam working thickness during shearer operation in the longwall face. Moreover, the comparison of the methane concentration for sensors that were located along the longwall in relation to the average concentration (Figure 10) from the multi-point system demonstrated similar characteristics, particularly for the sensor that was located at the closest location in relation to the multi-point system. These results confirmed that a sensor that is located close to the multi-point system truly captures the nature of changes in methane in the overall cross-section. Moreover, studies concerning the methane concentration and air volume distribution in the seam working thickness were performed using a multi-point system that revealed much higher methane emissions from the sidewall than from the goaf.

Acquiring new knowledge for recognizing the time and space distribution of the methane concentration in the longwall and adjacent galleries allows for the accurate determination of the methane volume that is flowing out of the longwall area. This is part of the entire volume of methane that is flowing from the mine through ventilation shafts to the atmosphere. In addition, the methane that is released from coal that is stored in heaps near mines and power plants also flows into the atmosphere. An additional source of methane in coal-fired power plants is methane emitted during grinding in the process of coal preparation for combustion in power plant boilers. Such methane sources can be investigated using aviation [18] and satellite [19] methods. The results of these studies prompted the comparison of methane emission through the shafts of hard coal mines with observations made with the use of aerial measurement techniques. There are also known research works on methane emission [20], and the results of their research allow for the forecasting of methane emissions.

6. Conclusions

To identify the methane hazard in the longwall, research experiments were carried out. Throughout, the air parameters were recorded during different operational cycles of the shearer by both the mine monitoring system and additional research equipment. The research confirmed the significant influence of the shearer’s operation on the longwall ventilation conditions. In particular, shearer operation was related to changes in the flow rate, and thus also the concentration of methane in the air ventilating the wall. The mining and crushing of coal increases methane emissions from the excavated material and the exposed coal. The movement of the longwall shearer in the longwall clearly disturbs
the air flow conditions and affects the methane-air mixing processes. Driving the shearer against the air flow direction causes an increase of the amount of air flowing into the goafs. Further this air returns to the longwall bringing additional methane from the goafs.

The phenomena that are described here have been confirmed in tests, in the monitoring system, and in an extended system with wireless methane meters that were placed along the wall. An important element of the presented results was the in situ tests that were carried out with the use of a multi-point system with many methane-anemometers installed on a truss that was placed in the cross-section of the wall. This allowed us to determine the space-time distribution of the air velocity and the concentration of methane in this cross-section. The use of the velocity-area method to determine the air volume flow that was based on local velocity measurements with the simultaneous measurement of methane concentration allowed us to determine the air and methane volume flows. This was much more accurate than the standard method of measuring the air volume flow by traversing and measuring the concentration of methane at one point of the excavation cross-section. The method and apparatus that were used were unique due to the environmental conditions in the longwall during the shearer operation. The elaboration of the results of the multi-point measurements with the use of the proprietary IZO-VM program allowed for the visualization of the space-time distributions of the air velocity and methane concentrations in the longwall cross-section. This provided information on the presence of local methane hazard zones in the longwall. The results of this research are of significant importance for the guidelines of the location of methane concentration sensors of the monitoring system in the longwall cross-sectional area, as well as along the length of the longwall depending on the methane inflow stream during cutting with a shearer and the amount of air flowing in the longwall.

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