Arch. Min. Sci. **64** (2019), 3, 467-485

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2019.129363

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METHODOLOGY FOR DETERMINING METHANE DISTRIBUTION IN A LONGWALL DISTRICT

METODYKA WYZNACZANIA ROZKŁADU WYDZIELANIA METANU W REJONIE ŚCIANY

This paper presents mathematical models enabling the calculation of the distribution and patterns of methane inflow to the air stream in a longwall seam being exploited and spoil on a longwall conveyor, taking into account the variability of shearer and conveyor operation and simulation results of the mining team using the *Ventgraph-Plus* software. In the research, an experiment was employed to observe changes in air parameters, in particular air velocity and methane concentration in the Cw-4 longwall area in seam 364/2 at KWK Budryk, during different phases of shearer operation in the area of the mining wall in methane hazard conditions. Presented is the method of data recording during the experiment which included records from the mine's system for automatic gasometry, records from a wireless system of eight methane sensors installed in the end part of the longwall and additionally from nine methane anemometers located across the longwall on a grid. Synchronous data records obtained from these three independent sources were compared against the recording the operating condition of the shearer and haulage machines at the longwall in various phases of their operation (cleaning, cutting). The results of the multipoint system measurements made it possible to determine the volume of air and methane flow across the longwall working, and, consequently, to calculate the correction coefficients for determining the volume of air and methane from measurements of local air velocity and methane concentration. An attempt was made to determine the methane inflow from a unit of the longwall body area and the unit of spoil length on conveyors depending on the mining rate. The Cw-4 longwall ventilation was simulated using the data measured and calculated from measurements and the simulation results were discussed.

Keywords: methane hazard, monitoring system, Mine ventilation, sources of methane inflow at the longwall

W artykule przedstawiono modele matematyczne pozwalające obliczyć rozkład i przebieg dopływu metanu do strumienia powietrza w ścianie z urabianego pokładu i urobku na przenośniku ścianowym z uwzględnieniem zmienności pracy kombajnu i przenośnika oraz wyniki symulacji pracy zespołu wydobywczego z zastosowaniem programu Ventgraph-Plus. W badaniach wykorzystano eksperyment obserwacji zmian parametrów powietrza, a w szczególności prędkości powietrza i stężenia metanu w rejonie

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ściany Cw-4 w pokładzie 364/2 KWK Budryk w czasie różnych faz pracy kombajnu w rejonie ściany wydobywczej w warunkach zagrożenia metanowego. Przedstawiono sposób rejestracji danych w czasie eksperymentu, który obejmował zapisy z kopalnianego systemu gazometrii automatycznej, rejestracje w systemie bezprzewodowych w liczbie 8 sztuk czujników metanu zabudowanych w końcowej części ściany oraz dodatkowo 9 sztuk meta-anemometrów zabudowanych w przekroju poprzecznym ściany na kratownicy. Synchroniczne zapisy danych pozyskane z tych trzech niezależnych źródeł porównano na tle zapisu stanu pracy kombajnu oraz maszyn odstawy w ścianie w różnych fazach ich pracy (czyszczenie, cięcie). Wyniki pomiarów systemem wielopunktowym pozwoliły wyznaczyć strumień objętości powietrza i metanu w przekroju wyrobiska ścianowego i w następstwie obliczyć współczynniki korekcyjne dla wyznaczania strumienia objętości powietrza i metanu z pomiarów miejscowych prędkości powietrza i stężenia metanu. Podjęto próbę wyznaczenia wielkości dopływu metanu z jednostki powierzchni calizny ściany oraz z jednostki długości urobku na przenośnikach w zależności od prędkości urabiania. Wykonano symulację przewietrzania ściany Cw-4 z wykorzystaniem zmierzonych i obliczonych z pomiarów danych oraz omówiono wyniki symulacji.

Słowa kluczowe: wentylacja kopalń, zagrożenie metanowe, system monitoringu, źródła dopływu metanu w ścianie

1. Introduction

To ensure correct results of the computer-aided simulation of ventilation in the longwall district with a running shearer, it is of essence to make a correct choice of the input quantities for the mathematical models used in the simulation software. These models describe relationships between such parameters of air venting the longwall as the volume streams and the volume percentage of methane in these streams. The *Ventgraph-Plus* Ventilation Engineer Software (Pritchard, 2010; Dziurzyński et al., 2013) enables calculation of air and methane distribution in the mine ventilation network using a database covering the ventilation network topology and parameters of its components, such as aerodynamic resistance and geometric dimensions of ventilation siding and gob, network nodes and air density in sidings, as well as the distribution of methane inflow sources. The sources of methane inflow at the longwall, with the shearer running, include the seam being exploited, spoil on conveyors, inflows from the gob of the longwall and adjacent gobs as well as from the seams located above and below. *Ventgraph-Plus* provides mathematical models enabling the calculation of the distribution and pattern of methane inflow to the air stream in a longwall seam being exploited and spoil on a longwall conveyor, taking into account the variability of shearer and conveyor operation. The distribution and pattern of methane inflow from the spoil on the conveyor in the main gate can also be calculated. Calculated streams of incoming methane make it possible determine time-varying distributions of methane concentration in the adjacent longwalls and headings. For those calculations, it is necessary to enter the input data into the software. That includes:

- methane content of the seam being exploited;
- trajectory of the shearer movement at the longwall taking into account the mining periods;
- the web and height of the seam being mined;
- conveyor speeds.

In order to establish the mentioned values, it is necessary to perform in situ measurements which are possible to perform during continued operation at the longwall (Schatzel et al., 2017). The paper presents the results of measurements of methane concentration and air velocity in the area of CW-4 longwall in the 364/2 seam at KWK Budryk. The recorded concentration patterns were obtained from methane detectors of the mine gasometry system and additional eight precise wireless methane detectors installed in the longwall. Furthermore, air velocities measured by mine anemometers were recorded along with air velocities and methane concentrations from by the multipoint system of air flow through nine meta-anemometers set in the end portion of the longwall, as shown in Figure 6 (Dziurzyński et al., 2014).

The results of the multipoint system measurements made it possible to determine the volume of air and methane flow across the longwall working, and, consequently, to calculate the correction coefficients for determining the volume of air and methane from measurements of local air velocity and methane concentration. For the selected period of time, methane concentrations measured in the longwall were correlated with the work schedule of the shearer. An attempt was made to determine the methane inflow from a unit of the longwall body area and the unit of spoil length on conveyors depending on the mining rate. The Cw-4 longwall ventilation process was simulated using the data measured and calculated from measurements and the simulation results obtained were discussed.

2. Modification of the *Ventgraph-Plus* software

In 2001, at the Mine Ventilation Laboratory IMG PAN, works were initiated to modify the *Ventgraph* software (Blecharz et al., 2003; Dziurzyński et al., 2013) to enable numerical modelling of the longwall with a running shearer. These works included the creation of a model of methane outflow from the longwall being mined and spoil removed (Dziurzyński et al., 2001). In the longwall model created then, the shearer worked at a constant speed and in one direction (Blecharz et al., 2003). In the following years, the model was expanded to include the operation of the shearer according to the saved schedule, with mining in both directions and with the shearer stops and the face and longwall conveyor. (Dziurzyński et al., 2008). Another version of the model allowed simulation of the shearer operation at a rate depending on the concentration of methane, measured in the air current flowing out of the longwall (Dziurzyński et al., 2018). Said model, after a few changes adapting it to the simulation of shearer operation and conveyors according to the saved schedule, was implemented in the *Ventgraph-Plus* software and used to simulate the measurement of changes in air parameters, in particular the measurement of air velocity and methane concentration in the area of the CW-4 longwall in the 364/2 seam at KWK Budryk (Wasilewski & Branny, 2008; Dziurzyński et al., 2014) during various phases of the shearer operation in the area of the longwall in conditions of methane hazard. The model described allows for simulating the movement of the shearer across the longwall and the operation of the face and longwall conveyors based on traffic parameters saved in a table. The common parameter for the shearer and conveyors is the time of changing the value of any of the other parameters, counted in minutes from the beginning of the simulation. The other parameters include:

- shearer position at the longwall, measured in meters from the longwall beginning;
- the speed of the shearer movement in m/min, where the sign of the speed value determines the direction of the shearer movement, the positive sign means the movement from the beginning to the end, while the negative sign means the movement in the opposite direction;
- mining indicator, value 1 means that the shearer cutting, 0 – not cutting;
- conveyor operation indicator, value 1 means that conveyors work, 0 – conveyors stopped.

The mining with a longwall shearer involves the phenomena of methane separation from the fracture zone, which forms in front of the shearer and the surface of the newly exposed face behind the shearer (Tarasow & Kolmakow, 1978; Schatzel et al., 2008). For numerical modelling of such phenomena, a simplified triangular shape of the relationship of methane emission volume per unit area was assumed in the models mentioned, as shown in Fig. 1, (Dziurzyński et al., 2018).

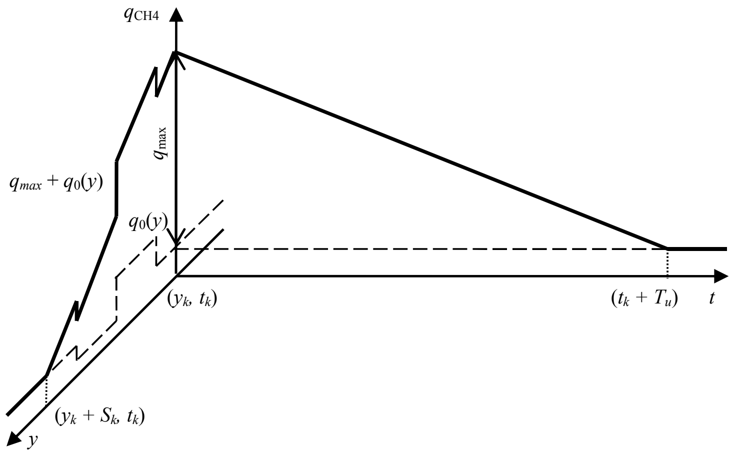

Fig. 1. Spatio-temporal relationship of methane release rate from the longwall cut with a shearer. Designation: y_k – location of the shearer at the longwall at time t_k; S_k – length of the fracture zone in front of the shearer; T_u – methane emission stabilisation time after opening new face surface; $q_0(y)$ – distribution of the initial value of the methane volume flow per area unit of the longwall, taking into account the variable gas distribution of the seam; q_{max} – increase of methane density of the volume stream at the mining site

Such a spatio-temporal relationship of methane release rate from the longwall cut with a shearer makes it possible to determine the distribution of methane release along the longwall at any time t, in which the shearer is located at a distance y_k from the longwall beginning (Fig. 2). In Fig. 2, an exemplary trajectory of the shearer movement is plotted in a solid bold line, and sections of the shearer's trajectory without mining are shown with a dotted bold line. The distribution of the methane release rate from the wall face $q_{CH_4}(y, t)$ is shown (dotted line) for the time t, when the shearer is located at a distance y_k from the beginning of the longwall with the length of L_s. This distribution shows examples of two methane velocity values at the distances of y_1 and y_2 from the beginning of the longwall. As shown, determining the velocity of methane release at the point (y_1, t) requires knowledge of the time t_{kp}, in which the shearer was located at a distance y_1 from the beginning of the longwall. To determine the value of the methane release velocity at the point (y_2, t), it is necessary to know the distance of the point (y_2, t) from the shearer position in the longwall y_k at the moment t. These relationships can be presented as follows:

$$q_{CH_4}(y_1) = q_0(y_1) + q_{max}\left(1 - \frac{t - t_{kp}}{T_u}\right) \tag{1}$$

$$q_{CH_4}(y_2) = q_0(y_2) + q_{max}\left(1 - \frac{y_2 - y_k}{S_k}\right) \tag{2}$$

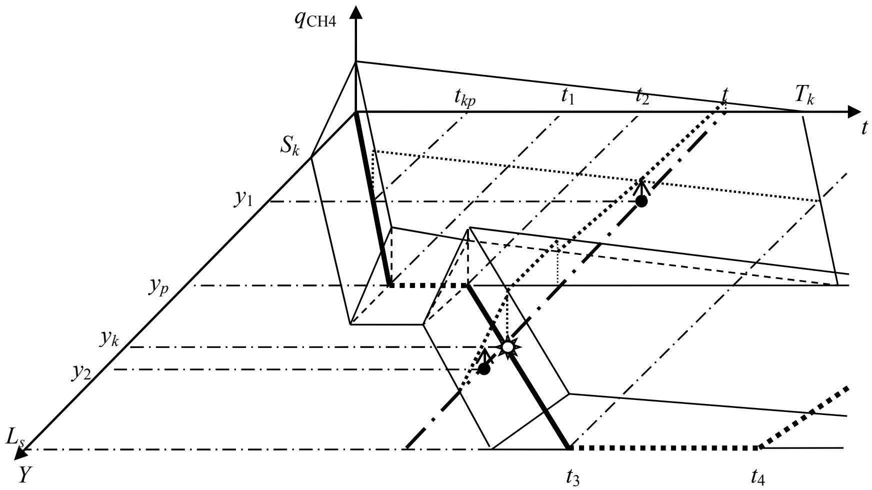

Fig. 2. Distribution of the methane volume stream density from the longwall face mined with a shearer with variable speed of movement and stops.
Continuous bold line – sections of the trajectory of the shearer, dotted bold line – sections of the shearer trajectory that is not cutting at the time $t_1 \div t_2$ and $t > t_3$.

Apart from methane released from the face of the longwall, methane from the extracted coal flows into the stream of air flowing through the longwall working. A model of coal degassing with exponential decrease of methane volume flow, presented in the article of Dziurzyński and Krach (2001), based on the work of Airuni (1987), and the relationship between the mass of spoil on the unitary conveyor section and shearer cutting parameters and the conveyor speed, based on the results of the work of Drzęźla and Badura (1980) was used to describe this inflow.

The linear density of spoil on a longwall conveyor equals:

$$g_s = \rho_w z H \frac{\left|v_k\left(t_s\right)\right|}{v_s + v_k\left(t_s\right)} \tag{3}$$

where

- ρ_w — density of coal being mined;
- z — shearer web;
- H — web height;
- $v_k(t_s)$ — shearer speed at the time t_s;
- v_s — longwall conveyor speed.

The linear density of spoil on conveyor in the gate road:

$$g_t = g_s \frac{v_s}{v_t} \tag{4}$$

where v_t — conveyor speed in the gate road.

Knowing the times of transport delays for spoil on a longwall conveyor τ_s and on the transport conveyor τ_t, it is possible to calculate the volume flow of methane from the mass unit of the spoil, and then, knowing the linear density of the spoil, from the unit of the spoil length on the conveyors.

Methane volume flow from the unit of the spoil length with a linear density g_s on a longwall conveyor $q_{CH_4\,ps}$ and on a transport conveyor $q_{CH_4\,pt}$ equals:

$$q_{CH_4\ ps/pt} = g_{s/t} \sum_{i=0}^{3} G_i \exp\left(-\frac{\tau_{s/t}}{\tau_i}\right) \tag{5}$$

where:

$$G_i = \frac{V_i}{\tau_i}, \quad i = 0, 1, 2, 3,$$

V_0, τ_0 — volume of the desorbed gas and desorption time constant from the volume of sorption particles;
V_1, τ_1 — volume of the sorbed gas and desorption time constant for gas accumulated on the surface of sorption particles;
V_2, τ_2 — volume of the sorbed gas and desorption time constant for the supersorption particles;
V_3, τ_3 — volume of the sorbed gas and desorption time constant from the volume of filtration and sorption particles;

whereby: $\tau_0 > \tau_1 > \tau_2 > \tau_3$.

The volumes mentioned above refer to the unit of coal mass.

The summarised mass stream of methane flowing into the air per the longwall length unit equals:

$$q_{M\ CH_4\ s} = \rho_{CH_4}\left(q_{CH_4\ ks} + q_{CH_4\ ps}\right) \tag{6}$$

where

ρ_{CH_4} — methane density;
$q_{CH_4 ks}$ — methane volume stream flowing from a length unit of the face of longwall being worked;
$q_{CH_4 ps}$ — methane volume stream coming from the unit of spoil length on the longwall conveyor.

The methane volume stream flowing from a length unit of the face of longwall at a distance y from its beginning equals

$$q_{CH_4 ks} = q_{CH_4}(y)H \tag{7}$$

where H — web height.

In order to simulate a specific case of shearer operation in the area of the CW-4 long wall in the 364/2 seam at KWK Budryk, it is necessary to enter, in the software, the parameters values as close as possible to the real ones. This is a major difficulty, because most of them are not measured directly. The measurements of methane concentration and air velocity recorded by the gasometry system can be utilised, remembering, however, that these are local measurements, requiring usually adjustments to obtain the average values in the section of the working. The results of manual measurements and multi-point measurements, performed as part of a measurement experiment can also be used.

3. Measurement data processing

From the measurement experiment in the area of the Cw-4 longwall in the 364/2 seam at KWK Budryk (Dziurzyński et al., 2014), performed during various phases of shearer operation, a series of methane concentrations and air velocities were obtained from the mine gasometry system, from wireless methane sensors additionally arranged along walls and from the multipoint methane anemometer system located at the bottom of the longwall. Furthermore, power supply records of the shearer and conveyors were available along with maintenance records of the shearer position at the longwall at a given time and working condition (cutting, not cutting) at that time. Based on that data, an attempt was made to reconstruct the trajectory and work schedule of the shearer at the longwall.

Recording of the shearer and longwall conveyor power supply status from 7:00 to 12:00 is shown in Fig. 3.

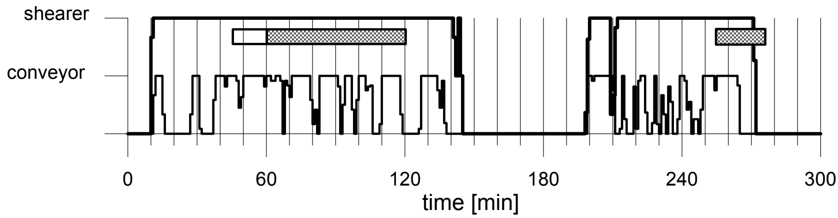

Fig. 3. Recorded work schedule of the shearer and longwall conveyor.
Rectangles indicate sections of the shearer working time according to the maintenance records.
Dashed rectangles – shearer cutting

The above figure shows a discrepancy, since the shearer power supply is switched off in the 270th minute (at 11:30) and that of the conveyor already in the 264th minute (at 11:24), which is in contradiction with the data from the service records (dashed rectangle). Using the above data, the trajectory of the shearer in the longwall and the work schedule of the shearer and conveyors, recorded in table 1, were assumed for simulation purposes.

The trajectory of the shearer recorded in this way is shown in Fig. 4.

In order to estimate the value of the density of the methane stream flowing from the longwall face and from the extracted coal, methane concentration patterns recorded by mine methane meters, placed 2 m from the inlet to the longwall (MM120), halfway the longwall (MM129) and 10 m from the longwall outlet (MM118) were used, in the time from 7:00 to 12:00, as shown in Figure 5.

The values of methane concentration are marked with points, measured every 1 minute. The continuous line shows the methane concentration patterns filtered with a symmetrical FIR 5th order FIR filter with weights of 0.2. Dashed rectangles mean sections of time when the shearer was cutting.

TABLE 1

Trajectory and work schedule of the shearer and conveyors

Number of value change No.	**Time changes KT, min.**	**Shearer position on the longwall KY, m**	**Velocity of shearer movement KV, m/min**	**Shearer cutting/ not cutting KU**	**Conveyors run/ stopped PS**
0	0	15	*0*	0	0
1	38	15	***10.227***	0	**1**
2	60	240	***–3.897***	**1**	1
3	120	14	***0***	**0**	**0**
4	126	14	*0*	0	**1**
5	135	14	*0*	0	0
6	200	14	***–1.4***	**1**	**1**
7	210	0	***0***	**0**	**0**
8	224	0	***10.0***	0	0
9	235	110	***9.286***	0	0
10	249	240	*0*	0	**1**
11	255	240	***–6.667***	**1**	1
12	264	180	***–6.429***	**0**	**0**
13	271	135	***0***	0	0

Remarks: The change in the values of the shearer conveyors' movement parameters is marked in bold.

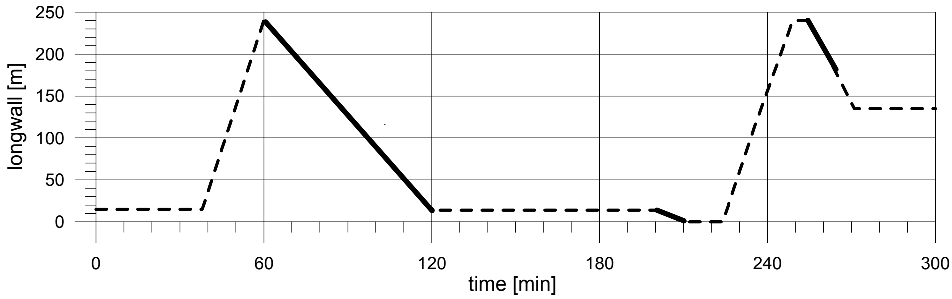

Fig. 4. The shearer path on the longwall with sections when it cuts marked with continuous lines

The volume stream of methane in the section distant by y from the beginning of the longwall and at the moment t can be calculated from the following equation:

$$q_{\mathrm{CH}_4}(y,t) = \int_y^L \left[g_k\left(y_p, t - t_o\right) + g_s\left(y_p, t - t_o\right)\right] dy_p + \\ + q_{\mathrm{CH}_4 wl}\left(L, t - t_{oL}\right) \qquad (8)$$

where:

$g_k(y_p, t - t_o)$ — linear density of the methane stream flowing in from the wall in the distance y_p from the beginning;

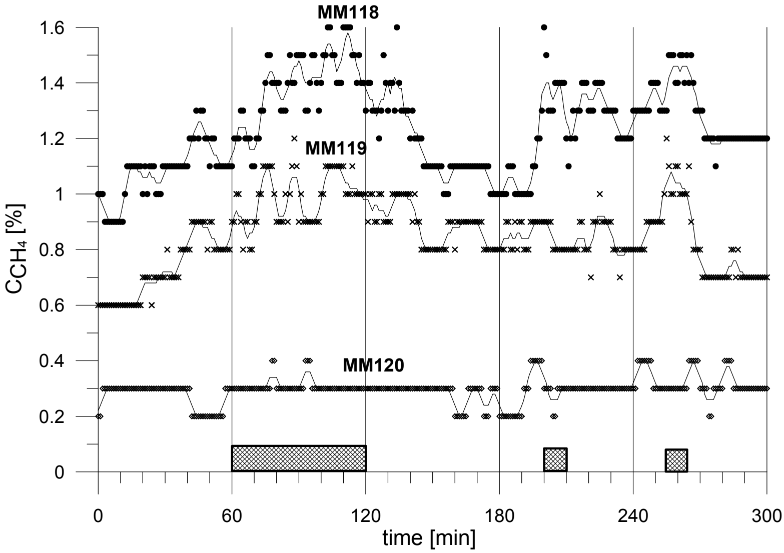

Fig. 5. Methane concentration patterns recorded by mine methane detectors, placed 2 m from the inlet to the longwall (MM120), halfway the longwall (MM129) and 10 m from the longwall outlet (MM118), in the time from 7:00 to 12:00

$g_s(y_p, t-t_o)$ — linear density of the incoming methane volume stream from spoil on a longwall conveyor;
t_o — transport delay at the section (y, y_p);
$q_{CH_4\,wl}(L, t_{o\,L})$ — methane volume stream at the inlet of the longwall;
$t_{o\,L}$ — transport delay at the section (y, L);
L — wall length.

The integration limits result from the fact that, in this exemplary simulation of a longwall with a shearer, the beginning of the y axis (along the wall) at the longwall outlet is assumed, i.e. the y axis is directed opposite to the direction of air flow at the longwall.

The transport delay is related to the lifting of methane with the air current at the longwall and is equal to:

$$t_o = \frac{y_p - y}{v_p}, \qquad t_{o\,L} = \frac{L - y}{v_p} \tag{9}$$

where v_p — air velocity at the longwall.

Further on, the index 1 was adopted for the values related to the MM120 methane detector at the longwall inlet, index 2 for the MM129 methane detector halfway the longwall and index 3 for the MM118 methane detector on the 10th meter from the longwall outlet. The methane stream at the inlet to the longwall can be calculated from the methane detector MM120. From Fig. 5, it can be concluded that the average value of methane concentration in 5 hours is equal to 0.3%.

Therefore, the methane stream at the inlet to the longwall is equal to:

$$q_{\mathrm{CH_4}\,wl1} = C_{\mathrm{CH_4}\,1} Q_{p1} \tag{10}$$

where: $Q_{p\,1}$ — air volume stream at the longwall inlet (in the y_1 section).

From the KWK Budryk model implemented in the *Ventgraph-Plus* software, the following air volume streams were obtained:

$$Q_{p\,1} = 1018.5 \text{ m}^3/\text{min}, \qquad Q_{p\,2} = 950 \text{ m}^3/\text{min}, \qquad Q_{p\,3} = 874.2 \text{ m}^3/\text{min}$$

Decreasing values of air stream flow in the wall result from air escapes to the gob. For the longwall cross-sectional area of 9 m^2 wall, the following air velocity figures are obtained:

$$v_{p\,1} = 113.2 \text{ m/min}, \qquad v_{p\,2} = 105.6 \text{ m/min}, \qquad v_{p\,1} = 97.1 \text{ m/min}$$

Therefore:

$$q_{\mathrm{CH_4}\,wl\,1} = 3.06 \text{ m}^3/\text{min}, \qquad q_{\mathrm{CH_4}\,wl\,2} = 2.85 \text{ m}^3/\text{min}, \qquad q_{\mathrm{CH_4}\,wl\,3} = 2.62 \text{ m}^3/\text{min}$$

To estimate the stream density of methane flowing in from the longwall face which is not being mined, for $q_0(s)$ in the equations (1) and (2), it was assumed that during the first 20 minutes there were not transient patterns associated with the settling time T_u and the exponential decrease of the methane stream from the spoil (Fig. 5), and the average values of methane concentration and the corresponding methane volume streams are equal to:

$$C_{\mathrm{CH_4}\,2} = 0.6\%,_4 \qquad q_{\mathrm{CH_4}\,2} = 5.70 \text{ m}^3/\text{min}, \qquad C_{\mathrm{CH_4}\,3} = 1\%, \qquad q_{\mathrm{CH_4}\,3} = 8.74 \text{ m}^3/\text{min}$$

Therefore, the equation (8) is simplified to the form:

$$q_{\mathrm{CH_4}\,i} = \int_{y_i}^{L} g_k\left(y_p\right) dy_p + q_{\mathrm{CH_4}\,wl\,i} \qquad \text{where } i = 2.3 \tag{11}$$

The linear density of the methane volume flow is given by:

$$g_k(y_p) = q_0(y_p) H \tag{12}$$

where: H — longwall height (H = 2 m here).

Assuming that densities of the methane stream from the face q_0 at the section of the wall from y_3 = 10 m to y_2 = 120 m and from y_2 to L = 240 m are constant, the following relationships are obtained:

$$q_{\mathrm{CH_4}\,2} = H \int_{y_2}^{L} q_{0\,2} dy_p + q_{\mathrm{CH_4}\,wl\,2} = q_{0\,2} H\left(L - y_2\right) + q_{\mathrm{CH_4}\,wl\,2} \tag{13}$$

$$q_{\mathrm{CH_4}\,3} = H\left(\int_{y_2}^{L} q_{0\,2} dy_p + \int_{y3}^{y_2} q_{0\,3} dy_p\right) + q_{\mathrm{CH_4}\,wl\,3}$$

$$= q_{0\,2} H\left(L - y_2\right) + q_{0\,3} H\left(y_2 - y_3\right) + q_{\mathrm{CH_4}\,wl\,3} \tag{14}$$

Thus, the initial density of methane volume stream for the longwall wall section (y_2, L) equals:

$$q_{0\,2} = \frac{q_{CH_4\,2} - q_{CH_4\,wl\,2}}{H(L - y_2)} \tag{15}$$

and for the longwall section (y_3, y_2)

$$q_{0\,3} = \frac{q_{CH_4\,3} - q_{CH_4\,wl\,3} - q_{CH_4\,2} + q_{CH_4\,wl\,2}}{H(y_2 - y_3)} \tag{16}$$

By substituting the above-mentioned to those equations, the following values are obtained:

$$q_{0\,2} = 0.012 \text{ m/min}, \qquad q_{0\,3} = 0.015 \text{ m/min}$$

It is more difficult to estimate the value of methane stream density increase during mining. From Fig. 4 and Table 1, it is concluded that the shearer begins cutting in the 60th minute from the position $y = L$ in the longwall, at a speed $v_k = 3.897$ m/min. It will reach the position y_k at the longwall, after the time:

$$\Delta t = \frac{L - y_k}{v_k} \tag{17}$$

The mining ends in the 120th minute, i.e. after 60 minutes, at the position $y_{k3} = 14$ m at the longwall.

From Fig. 5 and relationships (1) and (2) it follows that the highest value of methane volume stream at the longwall section at a distance of $y_3 = 10$ m from its beginning can be expected when the shearer is at the distance S_k from y_3, i.e. in the position $y_k = y_3 + S_k$ at the longwall. For $y_k = y_3$, the passage time of the shearer is 59 minutes, while the transport delay for this section is about 2 minutes. Thus, it is possible to ignore such delay in equation (8). In the methane stream coming into the air flowing in the wall, also the component originating from the spoil can be ignored, since, in this case, the transport of spoil takes place in the direction of the shearer mining, so the conveyor behind the shearer is empty. Stream of methane in the cross section of the longwall y_3, when $y_k = y_3 + S_k$ is equal to:

$$\begin{aligned} q_{CH_4\,3} = {} & H \int_{y_3}^{y_3+S_k} \left[q_{0\,3} + q_{max} \frac{y_p - y_3}{S_k} \right] dy_p + \\ & + H \int_{y_3+S_k}^{L} \left[q_{0\,3} + q_{max} \left(1 - \frac{y_p - y_3 - S_k}{v_k T_u} \right) \right] dy_p + q_{CH_4\,wl\,3} \end{aligned} \tag{18}$$

If $L - y_3 - S_k \le 2 v_k T_u$ the volume methane stream $q_{CH_4\,3}$ equals

$$q_{CH_4}(y_3) = H \left\{ \begin{aligned} & S_k \left(q_{0\,3} + \frac{q_{max}}{2} \right) + (L - y_3 - S_k) \times \\ & \times \left[q_{0\,3} + q_{max} \left(1 - \frac{L - y_3 - S_k}{2 v_k T_u} \right) \right] \end{aligned} \right\} + q_{CH_4\,wl\,3} \tag{19}$$

From here, the increase in the density of the methane volume stream at the time of mining can be calculated

$$q_{\max} = \frac{\dfrac{q_{CH_4\,3} - q_{CH_4\,wl\,3}}{H} - q_{0\,3}\left(L - y_3\right)}{\left(L - y_3 - S_k\right)\left(1 - \dfrac{L - y_3 - S_k}{2 v_k T_u}\right) + \dfrac{S_k}{2}} \tag{20}$$

If $L - y_3 - S_k > 2v_k T_u$ the volume methane stream $q_{CH_4\,3}$ equals

$$q_{CH_4\,3} = H\left[q_{0\,3}\left(L_u - y_3\right) + q_{\max}\frac{S_k + v_k T_u}{2} + \right] + q_{CH_4\,wl\,3} \tag{21}$$

The increase in the density of the methane volume stream while mining $q_{\max}$ can now be calculated as follows:

$$q_{\max} = 2\frac{\dfrac{q_{CH_4\,3} - q_{CH_4\,wl\,3}}{H} - q_{0\,3}\left(L - y_3\right)}{S_k + v_k T_u} \tag{22}$$

As it can be concluded from the above equations, the calculation of $q_{\max}$ is difficult, because, apart from the measured values of methane flow streams in the longwall cross-section, it is also necessary to know the length of the fracture zone in front of shearer S_k and the methane release stabilisation time from the opened body of coal behind the shearer T_u. That time can be estimated on the basis of the recorded drop in the methane concentration after mining is stopped.

From the pattern of methane concentration registered by the MM118 methane detector (Fig. 5), for the time after stopping mining in the 120th minute, the stabilisation time can be estimated with high uncertainty to be about 30 minutes.

Assuming also that for the fracture zone length $S_k = 10$ m, an attempt can be made to estimate the value of $q_{\max}$.

At first, the values $L - y_3 - S_{ku}$ and $2v_k T_u$ have to be calculated.

$$L - y_3 - S_{ku} = 240 - 10 - 10 = 220 \text{ m and } 2v_k T_u = 2 \times 3.897 \times 30 = 233.8 \text{ m}$$

The $L - y_3 - S_k \leq 2v_k T_u$ condition is met, so $q_{\max}$ is calculated using the equation (19).

From Fig. 5, the concentration of methane $C_{CH_4} = 1.6\%$ is determined, and the volume stream of methane is calculated

$$q_{CH_4\,3} = C_{CH_4} \times Q_{p\,3} = 1.6 \times 874.2/100 \approx 14 \text{ m}^3\text{/min}$$

Now, $q_{\max}$ can be calculated:

$$q_{\max} = \frac{\dfrac{14 - 2{,}62}{2} - 0{,}015\left(240 - 10\right)}{\left(240 - 10 - 10\right)\left(1 - \dfrac{220}{233{,}8}\right) + \dfrac{10}{2}} = \frac{5{,}69 - 3{,}45}{220 \cdot 0{,}059} = 0{,}17 \text{ m/min}$$

There are also model parameters associated with degassing of the spoil, i.e. volume streams of methane from a unit weight of spoil $_{i}G$, and decay time constants of these streams τ_{and} left to be determined. The data available in the literature (Airuni, 1987) can be used, or desorption measurements on carbon samples can be made.

4. An example of simulation of the ventilation process while mining with a shearer in the Cw-4 wall

The basis for the simulation is to develop of a numerical model adequate to the actual conditions for the considered case (Dziurzyński, 2009). The essential parameters can be obtained from ventilation measurements during the experiment (Dziurzyński et al., 2014), and they relate to air and methane flow in the wall and longwall workings as well the data which should be obtained based on the analysis of mining and geological conditions and theoretical considerations). With information on mining and geological conditions, a number of physical values were adopted, which constitute input data for the development of the numerical model.

Based on the data compiled, a numerical model of the longwall district was developed, which is shown in Figure 6. The Cw-4 longwall in the 364/2 seam, length 240 m, exploited longitudinally with fall of roof, ventilated to "Y", ensuring the discharge of used air from the longwall along the gob, average wall height 2.0 m, wall web 480 m. Methane hazard category IV, for the simulation, the calculated ventilation methane content in the amount of 38.4 [m^3/min] for the extraction of 1700 [Mg / day] was adopted.

The KSW-460NE shearer with electric feed drive operates at the longwall. The shearer harvester is designed for bi-directional mechanical cutting and loading of coal in a longwall pocketless system of, the web of the shearer 0.75-0.8 m, the speed of the shearer during cutting can change from 2.0 m/min to 20.0 m/min. Haulage at the wall is carried out with the Rybnik 850E260 scraper conveyor and PZP-KOBRA scraper conveyor. The speed of scraper conveyors

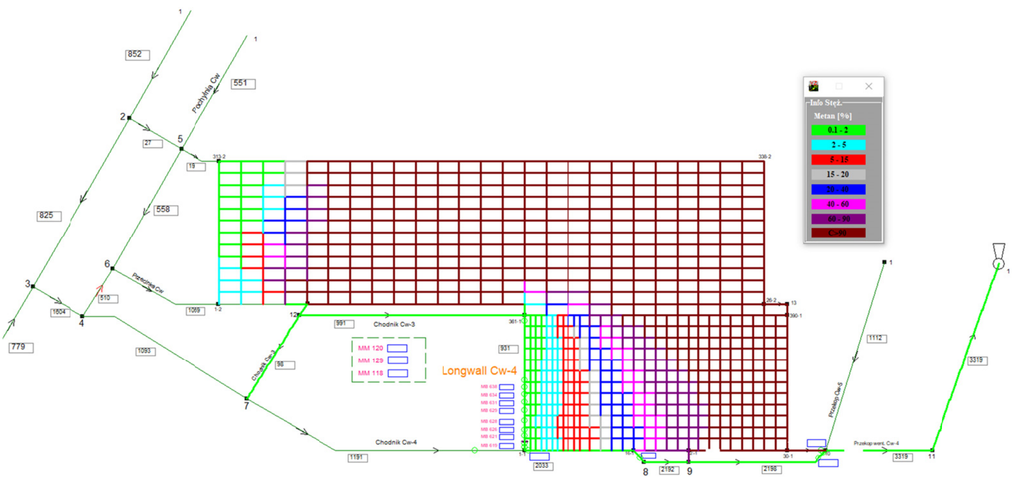

Fig. 6. Spatial layout of the Cw-4 longwall district, distribution of methane concentration in gob methane monitoring sensors, in rectangles – air volume m^3/min; – numerical model

is 91.8 m/min. Further haulage is carried out by Gwarek-1200 belt conveyor at speeds of up to 192 m/min.

The example under consideration refers to a shearer working at the Cw-4 longwall and taking away the spoil in methane inflow conditions, the schedule of which has been established on the basis of an analysis of shearer operation and information obtained from mine supervision staff and information on gas sensor records. The methodology of analysis and processing of measurement data is presented in section 3. In Fig. 7, with a bold violet line, the path of the shearer movement is shown at the Cw-4 longwall from 7:00 to 12:00.

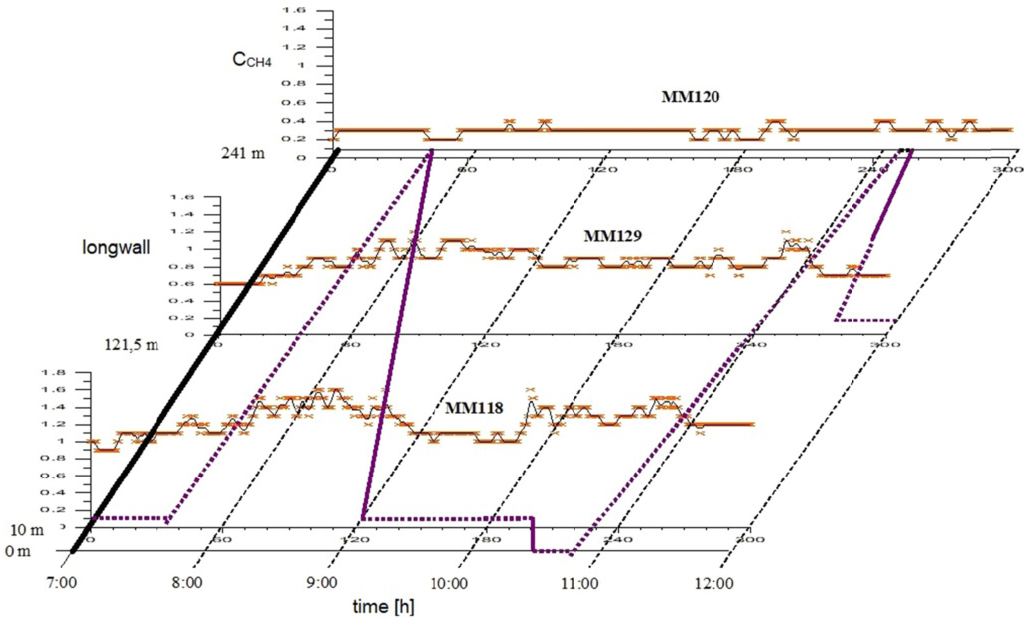

Fig. 7. Methane concentrations and shearer path – axonometry

Based on the experiment carried out in the mine and the patterns shown in Figure 7, in accordance with the requirements of the *VentGraph-Plus* simulation software, the schedule of the shearer operation and of the longwall and transport conveyors was established, which was adopted for further calculations.

Example:

Based on the information obtained, analyses carried out and the scheduling of the shearer's work, a numerical model of the Cw-4 longwall area was developed. For the purpose of this example, data files recorded by the MM gasometer system and the mobile sensor system MB were used, which were included in the *VentGraph-Plus* software procedures. This enables current comparison of the simulation results with the results of measurements during the experiment at Budryk mine. Table 2 presents the arbitrarily determined and adopted parameters of the mathematical model of methane emission, shearer operation and conveyors.

TABLE 2

Parameters for cutter-loader and conveyors

Parameter	Value
Loader-cutter web [m]	0.75
Longwall height [m]	2.0
Length of cutter-loader impact zone [m]	8
Initial speed of cutter-loader [m/min]	2.000
Speed of face conveyor [m/min]	60.00
Speed of conveyor in carrying gangway [m/min]	70.00
Stabilisation time of methane emission [min]	30
Initial speed of methane release [m/min]	7.80E-03
Highest speed of methane release [m/min]	2.100E-02
Coal density [kg/m3]	1300
Resistance in front of cutter-loader [kg/m7]	0.2
Change the cross-section on section with cutter-loader (lower by %)	25
Positive param. for f.conv	2.0
Positive param. for tr.conv..	4.2

Results of of air distribution calculations in the district and temporal changes of methane concentration at the Cw-4 longwall are shown in the following figures from 8 to 13, obtained by calculations (solid blue line), which were compared with the data recorded in the gasometer system (orange continuous line).

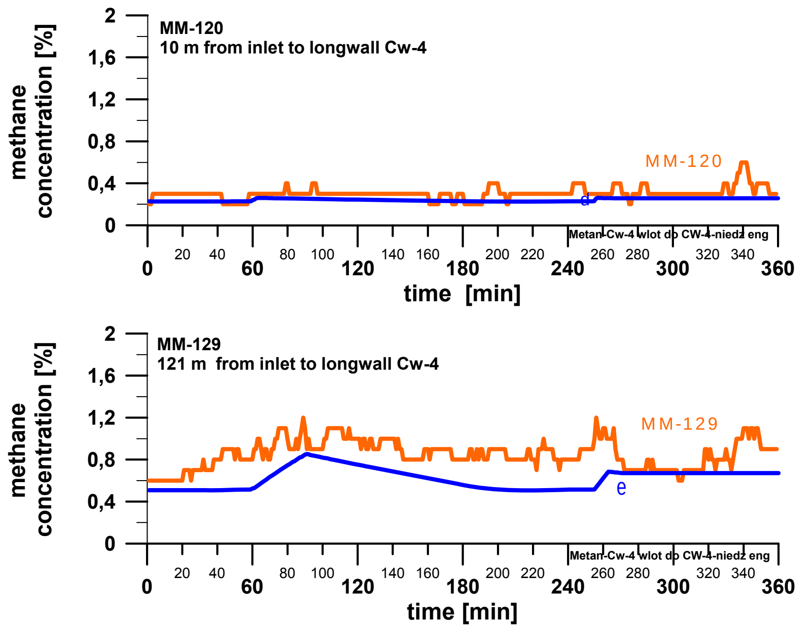

Fig. 8. Sensors of the gasometer system:
• 10 m from the inlet to the Cw-4 longwall; • 121 m from the inlet to the Cw-4 longwall

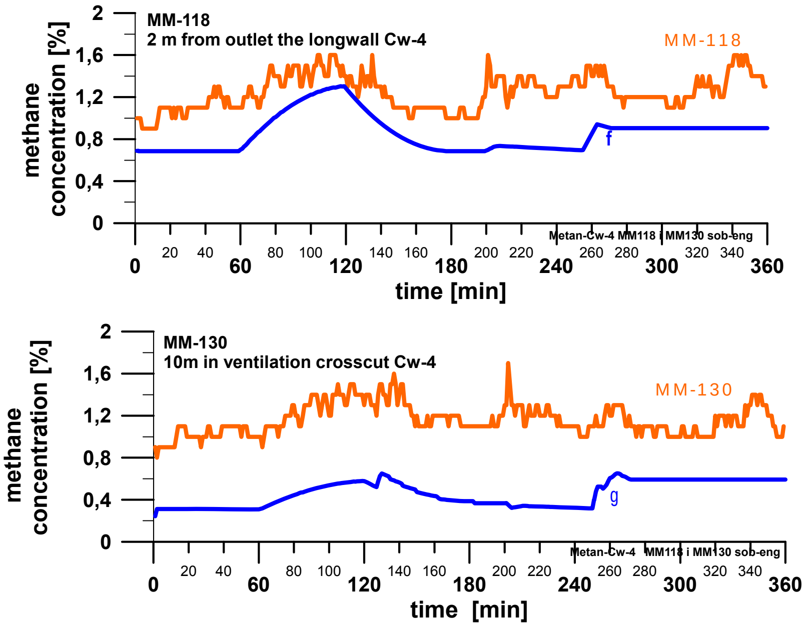

Fig. 9. Sensors of the gasometer system:
• 2 m from the outlet from the Cw-4 longwall; • 10 m in the Cw-4 heading behind the longwall line

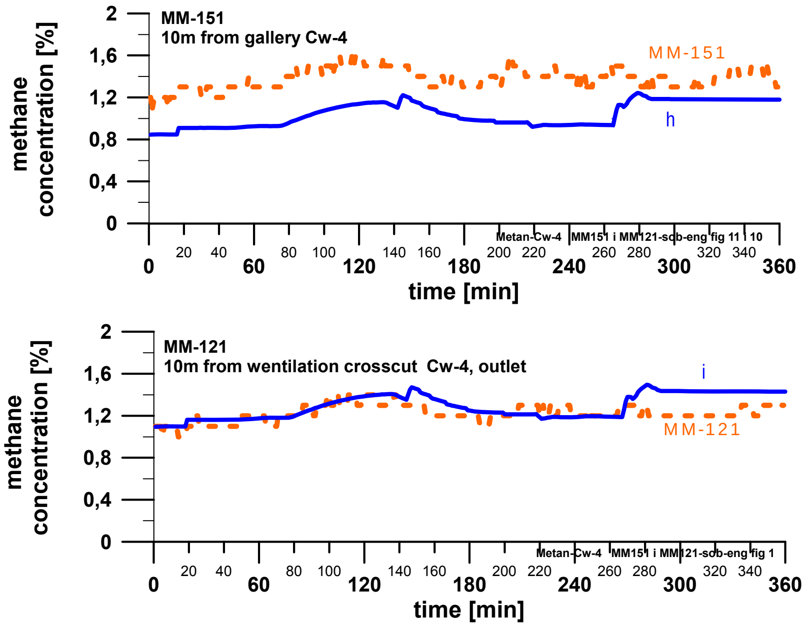

Fig. 10. Sensors of the gasometer system in the Cw-4 heading:
• 10 m from the Cw-4 heading; • 10 m from the ventilation cut

Figure 8 presents the changes in methane concentration at a distance of 10 m from the longwall inlet and at 121st metre at the Cw-4 longwall.

Figure 9 presents the changes in methane concentration at a distance of 2 m from the Cw-4 longwall outlet and at 10 m in the Cw-4 heading behind the longwall line. The chart shows a significant discrepancy between the simulation results and methane concentration changes recorded by the MM 130 sensor. Presumably, at that point, a stream of air and methane mixture flowing out of the wall and a refreshing current exiting the wall outlet did not cause the methane streams to mix with the flowing air.

Figure 10 shows the changes in methane concentration in the Cw-4 heading that discharges the used air at a distance of 10 m from the CW-4 heading and 10m from the ventilation cut.

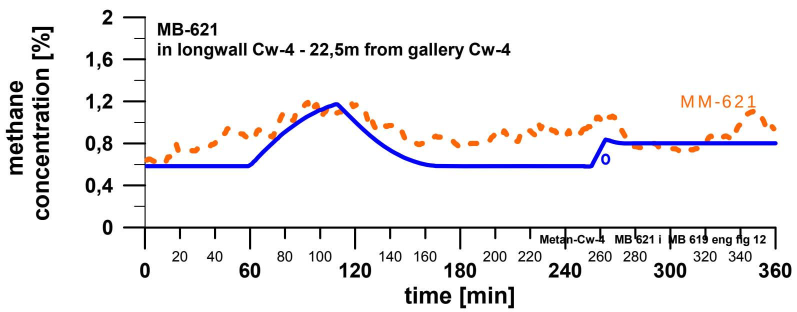

Fig. 11. Changes in methane concentration as detected by a mobile system sensor in the Cw-4 longwall; orange line – monitoring, blue line – simulation

Figure 11 shows changes in the methane concentration as detected by the mobile system sensor in the Cw-4 longwall at a distance of 22.5 m from the longwall outlet.

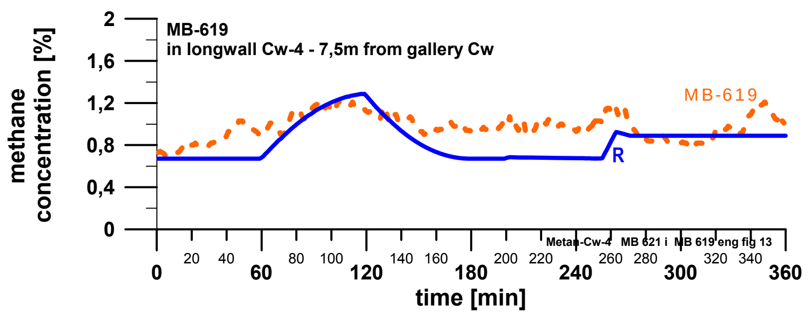

Fig. 12. Changes in methane concentration as detected by a mobile system sensor in the Cw-4 longwall; orange line – monitoring, blue line – simulation

Figure 12 shows changes in the methane concentration as detected by the mobile system sensor in the Cw-4 longwall at a distance of 7.5 m from the longwall outlet. Good consistency of time patterns of methane changes is observed.

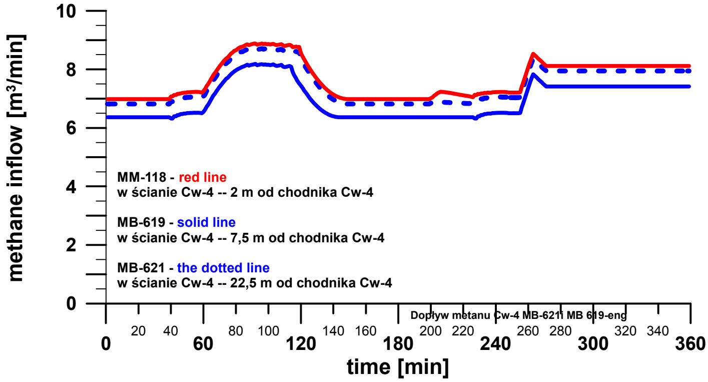

Fig. 13. Methane inflow in the Cw-4 longwall, gasometric system sensors

Figure 13 shows the changes in the amount of methane flowing at selected points at the Cw-4 longwall. The charts presented above confirm the possibility of determining both, changes in methane concentration and the flow of methane. Achieving good consistency of time patterns proves the correctness of algorithms and calculation procedures adopted in the ***VentGraph-Plus*** software.

5. Summary and conclusions

The results of the research showed the difficulties that occur when determining the parameters of the numerical model of the longwall and workings and gobs. The data obtained from the sensors of the mine's automatic gasometry mine system and experiments carried out are useful. The lack of reliable data on the shearer movement at the longwall (path, speed, mining condition) is quite noticeable. This can lead to significant differences between the registered methane concentration patters and concentration values obtained from simulations.

The ongoing development of the *VentGraph-Plus* software gives positive results as it takes into account further complex scenarios of the ventilation process analysis in the operating conditions of the mining set (shearer, conveyors, powered supports) during the exploitation of high-methane seams.

A numerical model of the Cw-4 longwall ventilated to "Y" with refreshment was built, the model parameters were selected, and the results obtained were compared with measurements of the monitoring system and measured parameters obtained during the methane concentration distribution experiment in the selected Cw-4 longwall section.

Acknowledgments

The research was conducted as part of the statutory works of the Strata Mechanics Research Institute, Polish Academy of Sciences in 2018, financed by the Ministry of Science and Higher Education.

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