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THE USE OF A UNIPORE DIFFUSION MODEL TO DESCRIBE THE KINETICS OF METHANE RELEASE FROM COAL SPOIL IN THE LONGWALL ENVIRONMENT

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Abstract: The unipore methane diffusion model based on the solution of the second Fick's law describes effectively the kinetics of methane release from coal grains. The knowledge of the model describing the kinetics of methane release from coal, the coalbed methane content, the sorption isotherm, the effective diffusion coefficient and the coal particle size distribution, enables the calculation of the volume of methane which is released from the coal spoil as a function of time. These assumptions became the basis for building the software that enables the analysis of methane emissions from coal during the longwall mining. Simulations were performed to determine the temporal and spatial methane inflow to the longwall. The share of methane emission from coal grains (taking into account both the emission kinetics and mass participation) of various classes has been analyzed. The results of the analysis showed that the methane from the small grains, in particular less than 0.1 mm in size, prevails. The mass fraction of these grains in the total weight does not exceed 5%. For the typical parameters determining the mining, geological and technological conditions of methane emissions at different moments of time and position of the longwall were determined.

Key words: *methane emission, methane emission forecast, methane hazard, methane content*

1. INTRODUCTION

According to the annual report on basic natural and technical hazards in hard coal mining issued by GIG [5], the amount of hard coal mined in Poland in 2014 was 72 514 thousand Mg, and the total methane emission was 891.1 million m^3 CH_4/year. Based on this data the relative methane emission in coal mines was determined, which amounted to 12.3 m^3 CH_4/Mg. In the years 2009–2014, there were 18 events related to methane ignition or explosion, as a result of which 25 miners died, 40 suffered severe and 31 minor injuries. Methane ignition was ranked first among the main causes of fatal and severe accidents in mining in 2014. One of the basic methods for assessing the potential methane hazard in longwall working areas is a reliable methane emission forecast based on knowledge and experience. It makes it possible to choose active and passive preventive measures for methane (Skoczylas, Wierzbicki [8], Skoczylas [10]). Total emission of methane in the working area includes methane from the longwall body, methane from the lower and upper coal seams and methane from the goaf and from the coal spoil in the longwall. The share of individual components of the total methane that reach the working area depends on many factors, such as:

- longwall geometry,
- coalbed methane content,
- ventilation method,
- structure of rocks surrounding the exploited seam, especially the neighbouring coal seams,
- properties of the coal-methane system,
- strength parameters of coal,
- mining method,
- methane outgassing activities and other.

In this study, the authors focused on methane reaching the longwall working area from spoil formed in the working process. Coal mining involves destruction of its structure and fragmentation to transport it to the surface. As a result of mining, spoil with specific granulation is obtained. Grain size distribution is a very important parameter. The amount of methane released within a given time from coal grains depends on the square of the grain radius (Skoczylas [9]). The knowledge of the model describing the kinetics of methane release from coal, the coal seam methane content, the sorption capacity of coal, the coal diffusion coefficient and the grain size distribution curve of the spoil, made it possible to calculate the volume of methane released from the spoil as a function of time.

This sentence can be treated as a thesis put forward in the present study.

The following assumptions were made in this study for the analysis of the quantity of methane released from spoil:

- – longwall shearer and a face conveyor are moving along a face of the longwall with constant, known direction and speed,
- there is pressure drop from coal seam pressure to atmospheric pressure of the moment of coal crushing,
- grains of coal in spoil have a spherical shape,
- the granulometry of the spoil along the whole longwall is known and constant,
- the solution of the second Fick's law can be used for description of methane release from the coal,
- sorption properties at the coal seam temperature are known, such as:
  - coalbed methane content,
  - sorption capacity under the atmospheric pressure,
  - the adsorption isotherm of methane,
  - diffusion coefficient of coal D_e,
- sorption capacities remain unchanged during production cycle being analysed,
- all processes are isothermal.

The experience gained at the Strata Mechanics Research Institute when analysing the phenomena occurring in the coal-methane system makes it possible to define the influence of factors such as the deposit temperature, the material composition, the moisture content in the coal, its sorption capacity and kinetic properties of the accumulation process as well as methane emission from coal (Wierzbicki 13]).

The issue of methane quantity assessment appeared in a study by Klebanov [1974]. A broader analysis was undertaken by Koptoń [6]. He takes only one radius for description of spoil. Dziurzyński et al. [2], [3] in a wider study covering all the way flow of methane into the mining excavation, account a factor from the spoil using Tarasov and Kolmakov's solution [12].

2. PHYSICAL BASIS OF THE MODEL OF METHANE EMISSION FROM THE SPOIL DURING LONGWALL EXTRACTION

In the study, methane emission from mined coal during longwall exploitation was considered. It was assumed that the only mechanism of methane emission is diffusion from coal grains (Gawor, Skoczylas [4]). The unipore diffusion model derived from Fick's second law was used

$$\frac{\partial \phi(r,t)}{\partial t} = \frac{D}{1+\Gamma} \cdot \nabla^2 c(r,t) = D_e \cdot \nabla^2 c(r,t) , \qquad (1)$$

where

$c\left[\frac{\text{mol}}{\text{m}^3}\right]$ – substance concentration,

t [s] – time,

$D\left[\frac{\text{m}^2}{\text{s}}\right]$ – diffusion coefficient,

$D_e\left[\frac{\text{m}^2}{\text{s}}\right]$ – effective diffusion coefficient $D_e = \frac{D}{1+H}$,

Γ [–] – slope coefficient in Henry's sorption isotherm,

r [m] – distance from the centre of the grain,

Taking the aforementioned assumptions of the model, Crank [1] provided an analytical solution to Eq. (1) (Wierzbicki, Skoczylas [14]) in the form

$$m(t) = \frac{6M}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 \cdot D_e \cdot \pi^2 \cdot t}{R^2} \right), \qquad (2)$$

where

M [g] – the total weight of gas deposited in grains,

m(t) [g] – the weight of gas deposited in a given time t,

R [m] – is the substitute grain radius determined on the basis of the following relation:

$$R = \frac{1}{2} \sqrt[3]{\frac{2 \cdot d_1^2 \cdot d_2^2}{d_1 + d_2}} , \qquad (3)$$

where d_1 and d_2 are the limits regarding the size of grains from the analyzed grain fraction.

Considering the usual size of the longwall and the speed of the shearer and conveyor, coal grains remain within the longwall area no longer than a few minutes. For typical values of the effective methane diffusion coefficients for Upper Silesian Coal Basin (USCB), we will deal with the analysis of the initial phase of methane emission. For description of this process it is necessary to take into account at least several terms of the series (Fig. 1). If we are also interested in the first seconds of emission, there should be several dozen expressions (Fig. 2).

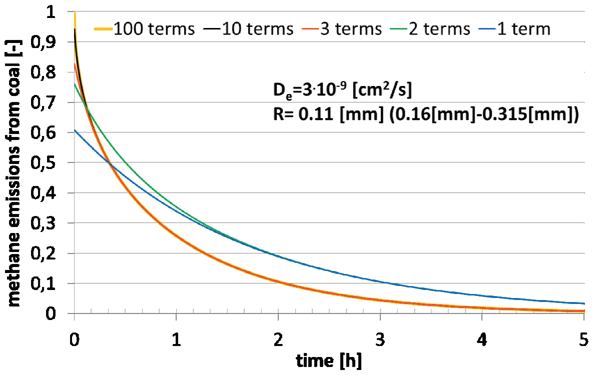


Fig. 1. The influence of terms of the series, which is the solution to the unipore model, on the quality of the model of methane emission from coal

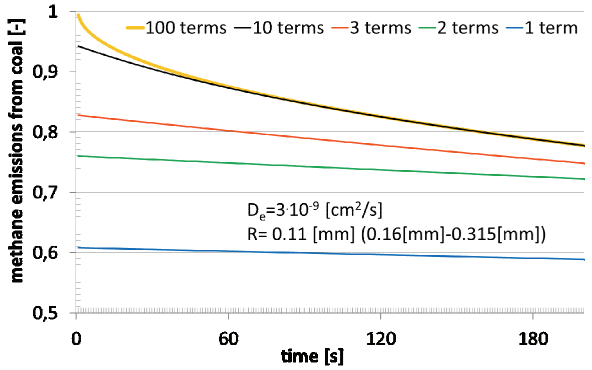


Fig. 2. The first 200 seconds of the course of methane emission from coal described by the unipore model with a varying amount of terms of the series

The simulation of emission assumes analysis of a single trip of a longwall shearer. At the moment $t_0 = 0$ s, the conveyor remains empty and shearer moves from the location $x_0 = 0$ m. The end of the simulation corresponds to the moment the shearer has travelled the entire length of the longwall and the entire spoil has left the longwall area on the conveyor. It is possible to analyse a case in which the shearer moves in the same direction as the conveyor (Fig. 3), or in the opposite direction (Fig. 4), changing the position from the last metre of the longwall to $x_0 = 0$ m.

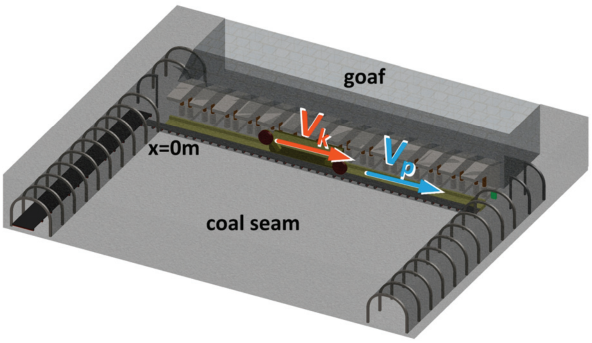


Fig. 3. Consistent direction of shearer and conveyor speed vectors

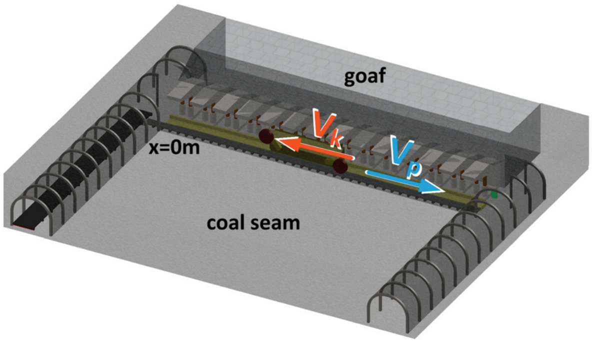


Fig. 4. Opposite direction of shearer and conveyor speed vectors

The spatial discretization the resolution of 1 m, was adopted while in temporal discretization it was 1 s. Temporary position of the shearer a product of the shearer speed and time, the motion being uniform. Every second, the algorithm adds a new fragment of the coal spoil in the starting position, which corresponds to the current shearer position, which will travel on the conveyor. Each fragment emits methane in accordance with the unipore model solution (2); however, the time at the beginning of the diffusion specifies the moment of its detachment from the rock mass, while the position is the sum of the shearer position at the moment of detachment and the product of the conveyor speed and time calculated from the detachment. Every second, a portion of methane determined on the basis of the model is added to each detached fragment in calculated quantities.

The model makes it possible to simulate methane emission from n grain classes of coal. Methane emissions are calculated using the following equation

$$m(t)=\sum\nolimits_{i=1}^{n}[u_i m(t,R_i)] \tag{4}$$

where:

R_i [m] – the substitute grain radius (3), representing individual grain classes,

u_i [%] – the percentage of individual grain classes.

A simulation of methane emission from mined coal during longwall exploitation was conducted. The following parameters of the analysis were adopted

- shearer web depths: 0.8 m,
- coal seam thickness: 2 m,
- longwall length: 200 m,
- shearer speed: 0.1 m/s,
- conveyor speed: 1 m/s,
- coal bed methane content Mn: 8 m^3 CH$_4$/Mg,
- sorption capacity a: 3.0 m^{3}CH$_4$/Mg,
- effective diffusion coefficient D_e: $3\cdot10^{-9}$ cm^2/s,
- number of grain classes: 10,
- number of expressions in a series (2): 100,
- grain composition curve: Fig. 5.

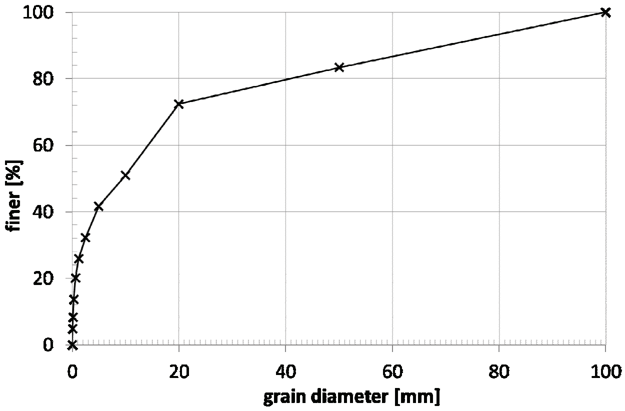


Fig. 5. Grain composition curve for the spoil from the longwall

The sieve test was the basis for determining the grain composition of the coal material collected from the first belt conveyor serving the longwall at the "Borynia–Zofiówka–Jastrzębie" hard coal mine. If we assume that the face conveyor transports the spoil at 1 m/s, then the mined coal should not remain in the longwall area longer than 200 s if the longwall is 200 m long. A diagram (Fig. 6) presents the kinetics of methane emission from coal grains with replacement radii corresponding to the sieved grain classes. For pieces of coal larger than 1 cm, methane emission will not exceed 0.5% of the originally accumulated methane over 200 s.

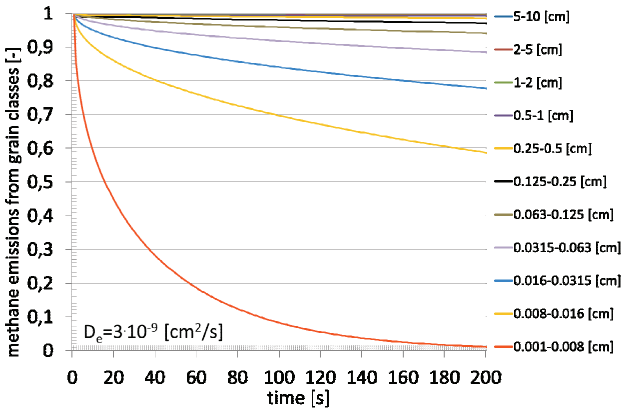


Fig. 6. Kinetics of methane emission from individual grain classes

When analysing methane emission from the spoil, it is important to take into account both kinetics of methane emission from coal from individual grain classes as well as the mass share in the entire spoil. Figure 7 presents the percentage of methane released from individual grain classes of the spoil over 200 seconds. The share of the lowest classes predominates, in particular below 0.1 mm despite the fact that the mass share does not exceed 5%.

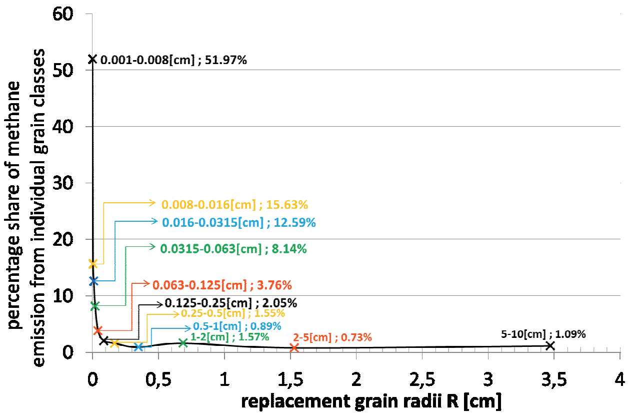


Fig. 7. The percentage share of methane emission
from the spoil from individual grain classes,
taking into account the kinetics of emission and the mass share
of individual classes over the first 200 seconds of the process

Using the model presented (Skoczylas, Wierzbicki [11]), which was implemented in a computer program with the discussed assumptions and parameters being discussed, simulation of methane emission was conducted during a full trip of the shearer in the same direction as the conveyor and in the opposite direction. Figure 8 presents accumulated methane emission as a function of distance from the beginning of the longwall (consistent direction). Every second of the simulation, part of the spoil with the grain size distribution curve presented in Fig. 5 is added, which is detached from the coal rock mass at the place calculated by means of motion equations for the shearer. Next, the amount of methane from the analysed fragment is calculated which was emitted over a few consecutive seconds, at places calculated on the basis of the initial position of the combine, at the detachment moment and motion equations for the shearer that describe the analysed fragment of the spoil. This cycle is repeated for each fragment of the detached spoil every second. Partial methane emissions from fragments of the spoil are cumulated in individual places on the longwall.

Figures 8 and 9 present cumulated methane emission at individual times of the experiment for the same and opposite directions of the shearer and conveyor motion. In all the cases of the experiment parameters being discussed, no more than 1 m³ CH_4 was emitted from the spoil. Curves, which are marked in different colours in the graphs, make it possible to observe cumulated methane emission as time functions for selected one-metre sections on the longwall. For example, the position corresponding to the half of the longwall length is marked in yellow in Fig. 8. Over the first 100 seconds, methane emission on the hundredth metre equals zero as the spoil on the conveyor (1 m/s) has not reached this place yet. From the hundredth second, a slow increase in cumulative emission can be observed as the spoil is being transported over the hundredth metre. As methane emission comes mostly from the smallest fractions (Fig. 7) which release methane very fast (Fig. 6), hence, the increase in emission is the most dynamic as the shearer comes close to the hundredth metre, and the time which lapses between the detachment of the fragment of the spoil and its transport is close to zero.

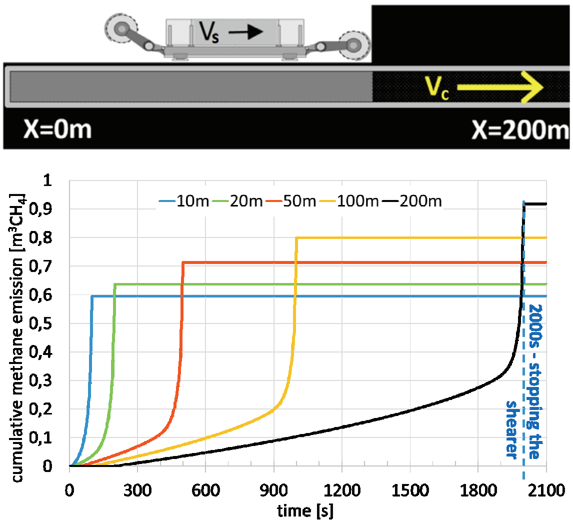


Fig. 8. Cumulative methane emission as a function of time for selected positions of the longwall length – the same direction of the shearer and conveyor

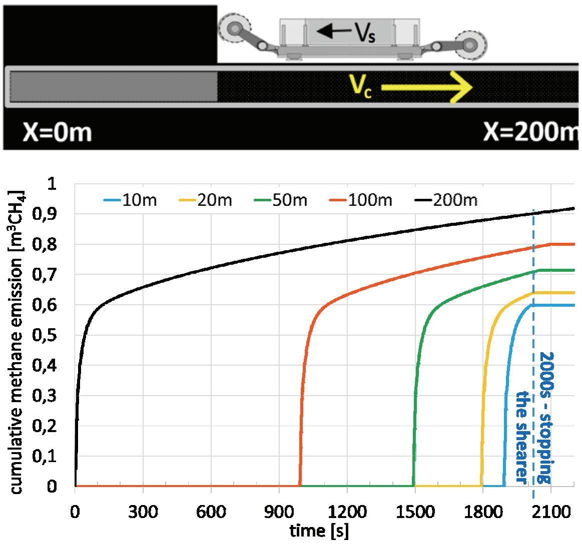


Fig. 9. Cumulative methane emission as a function of time for selected positions of the longwall length – opposite direction of the shearer and conveyor

In the hundredth second, the shearer (0.1 m/s) appears on the 100th metre. After passing this position, the cumulative emission per metre remains unchanged until the shearer reaches its end position at the longwall.

If we consider methane emission in the case of the opposite direction of the shearer relative to the conveyor (Fig. 9), the simulation lasts 200 seconds longer than for the consistent direction (Fig. 8). This results from the fact that the shearer, while travelling from the 200th metre of the longwall, reaches the zero position after 2000 seconds (0.1 m/s). The last portion of spoil detached from the coal rock mass is transported by a face conveyor towards the longwall at 1 m/s, leaving the longwall area after another 200 seconds. The red curve in Fig. 9 means temporary variability of cumulative methane emission at the location corresponding to the half of the length of the longwall (100 m). From the beginning of the simulation up to the 1000th second, cumulative emission amounts to zero at this point as the shearer, while moving (0.1 m/s) from the end of the longwall (200 m) reaches this point only after 1000 seconds, while the spoil is transported by the conveyor towards the end of the longwall. After 1000th second in the 100th metre of the longwall, the most dynamic increase in cumulative methane emission is observed as the shearer situated at a close distance supplies spoil detached from the rock mass shortly before it is transported to the 100th metre. As the shearer is moving further, the time that lapses between the detachment of coal and its transport to the 100th metre is extended, which, with regard to the enormous rate of methane emission for the lowest grain classes (Fig. 6), explains the slower increase in cumulative emission. After the shearer stops (2000 s), for 100 seconds still on the hundredth metre of the longwall, an increase in cumulative emission occurs as the spoil from the first metres of the longwall is moved on the conveyor. After the 2100th second, no increase in cumulative emission is observed any more at the half of the length of the longwall as the last fragment of detached coal from the first metre of the longwall has gone over the hundredth metre of the longwall on the conveyor.

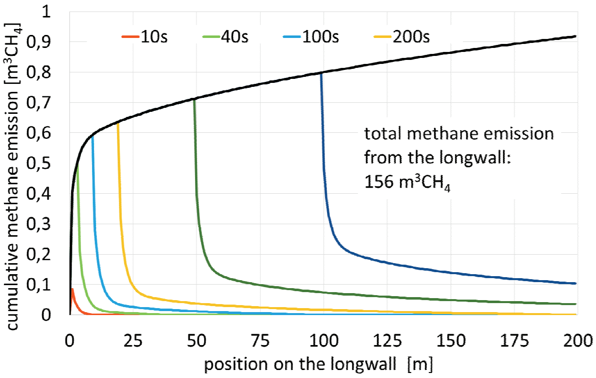


Fig. 10. Cumulative methane emission in the position on the longwall function for selected times – the same direction of the shearer and conveyor

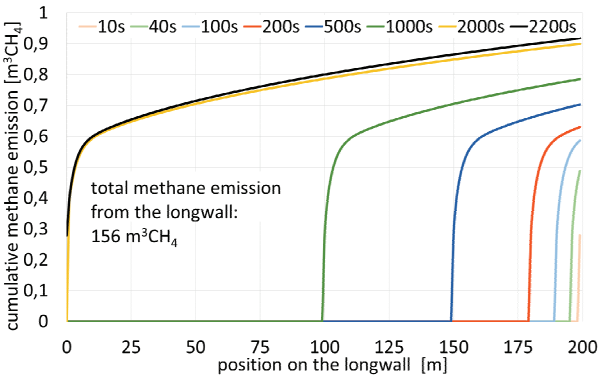


Fig. 11. Cumulative methane emission in the position on the longwall function for selected times – the same direction of the shearer and conveyor

Figure 10 presents cumulative methane emission against the position on the longwall function for the same direction of the shearer and the conveyor. Curves, which are marked with different colours, correspond to cumulative methane emission for selected time moments on individual metres of the longwall. For example, the blue curve, which illustrates cumulative emission in the 100th second from the moment the work is started, shows high dynamics of the increase in cumulative emission along the first few metres of the longwall, i.e., at a distance travelled by the shearer (0.1 m/s) over 100 seconds. Over the further metres, the value of cumulative emission decreases – the shearer up to the 100th second did not exceed the position of the 10th metre and the entire methane comes from emission from the spoil on the conveyor. At a distance above the 100th metre, the cumulative emission in the 100th second amounts to zero, as the face conveyor (1 m/s) has not provided the spoil there yet.

There is a course for the opposite direction of the shearer and the conveyor. For example, the blue curve is the cumulative emission in the position function on the longwall for the 500th second. As the combine is moving from the 200th metre to the beginning of the longwall, after 500 seconds it has travelled 50 metres and reached the position of the 150th metre, counting from the beginning of the longwall. The conveyor carries the spoil towards the end of the longwall so emission, are equal to zero below the 150th metre in the 500th second. In the 2000th second (yellow curve), the shearer finds itself at the beginning of the longwall. The simulation continues for another 200 seconds, as there is still spoil on the conveyor (1 m/s). Emission from the spoil that stays on the conveyor after the shearer stops are included on the black curve for the 2200th second.

If methane emissions are summed up every metre of the longwall during the simulation, it will be possible to define the total methane emission from the longwall as a function of time. Figure 12 presents cumulative methane emission from the entire longwall as a function of time for the same direction of the shearer and conveyor, while Fig. 13 depicts an analogous dependence for the opposite direction. The graphs are similar; however, it can be observed that up to the 2000th second, the derivative of the graph for the same direction decreases slightly while a decrease is observed for the opposite direction. The cumulative quantity of methane emitted from the longwall in the 2000th second is slightly higher for the same direction. After the 2000th second for the same direction of the shearer and conveyor, the entire spoil is already situated outside the longwall while a slight increase of cumulative emission can be observed for the opposite direction. The moment the observation is finished, the values of total methane emission from the longwall are identical – they do not depend on the mutual direction of the shearer and the conveyor; however, they are achieved at different times.

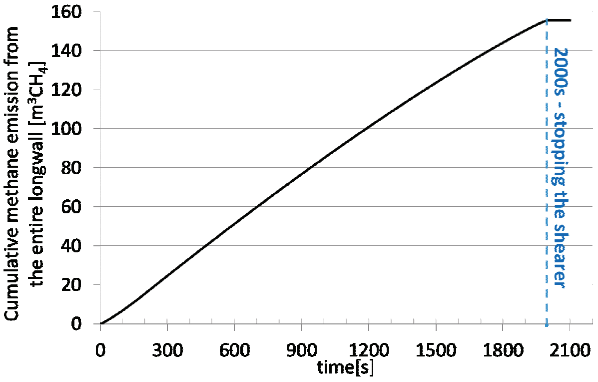


Fig. 12. Cumulative methane emission from the entire longwall as a function of the time – the same direction of the shearer and conveyor

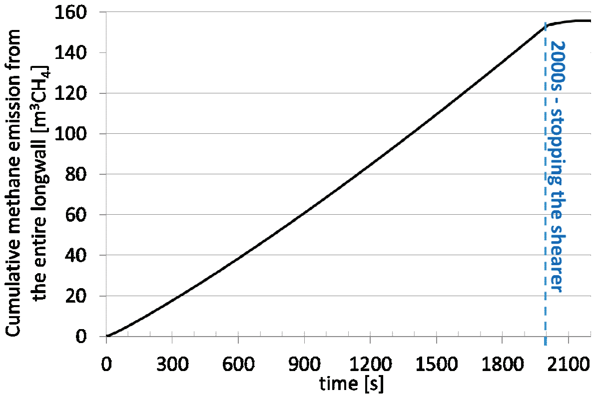


Fig. 13. Cumulative methane emission from the entire longwall as a function of time in the time function – opposite direction of the shearer and conveyor

Total methane emission from the longwall during a single working cycle in the presented example presented amounted to 156 m^3 CH$_4$. It is a relatively high amount – to obtain methane concentrations that do not exceed 2%, taking into account only methane from the spoil, 234 m^3 of air must be supplied every minute.

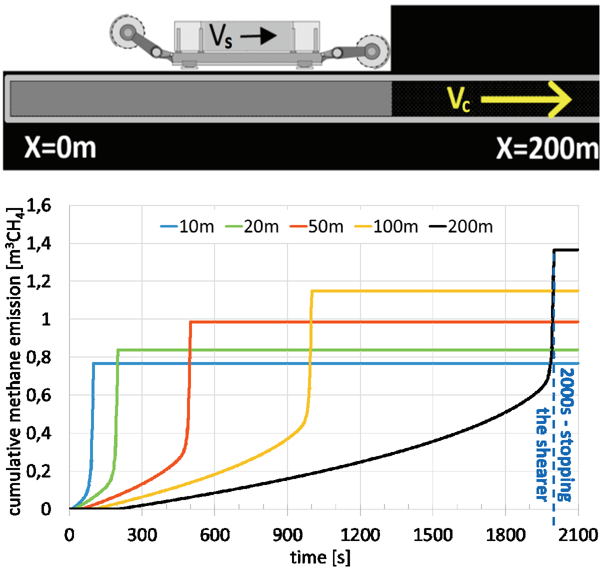


Fig. 14. Cumulative methane emission as a function of time for selected positions of the longwall length – the same direction of the shearer and conveyor – temperatures above 20 °C

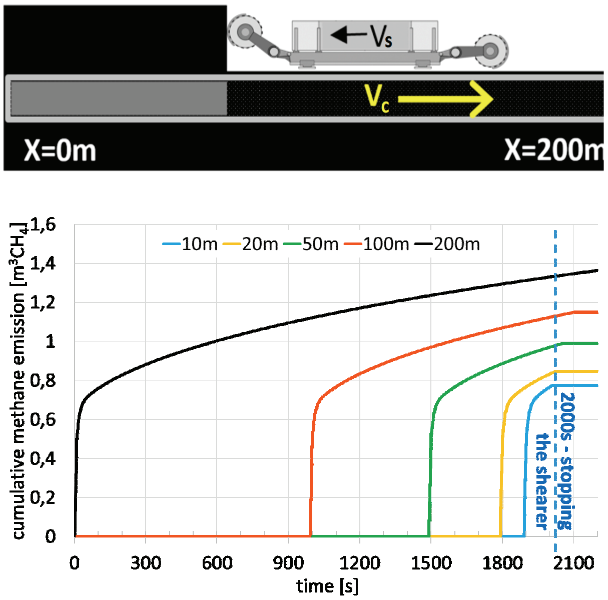


Fig. 15. Cumulative methane emission as a function of time for selected positions of the longwall length – opposite direction of the shearer and conveyor – temperatures above 20 °C

The initial temperature of the rock mass increases as deeper deposits are reached. The geothermal degree for GZW is approximately 33 m/°C. For coal seams at depths of approximately 600 m, it can be assumed that the rock temperature is approximately 25 °C. At this temperature, the analysed values of sorption parameters ($D_e = 3.10^{-9}$ cm^2/s, $a = 3$ m^3 CH$_4$/Mg) can be defined as typical. If we go down to deposits at a depth of approx. 1250 m, the temperature of the rock will go up by approximately 20 °C. Wierzbicki [13], [15] specifies how the effective diffusion coefficient and

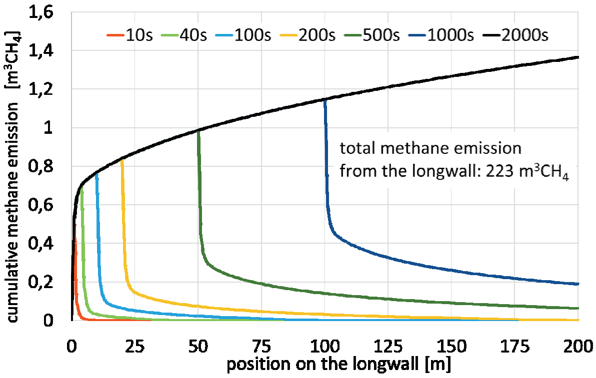


Fig. 16. Cumulative methane emission in the position on the longwall function for selected times – the same direction of the shearer and conveyor – temperatures above 20 °C

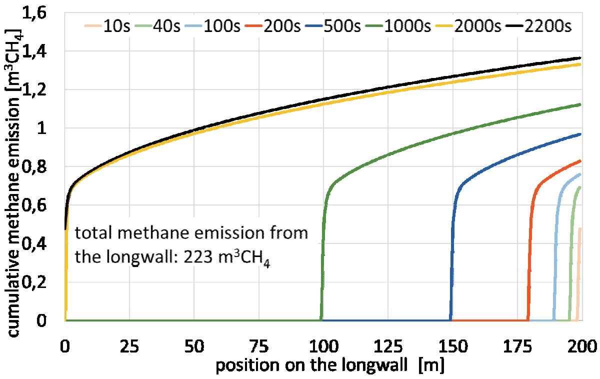


Fig. 17. Cumulative methane emission in the position on the longwall function for selected times – the same direction of the shearer and conveyor – temperatures above 20 °C

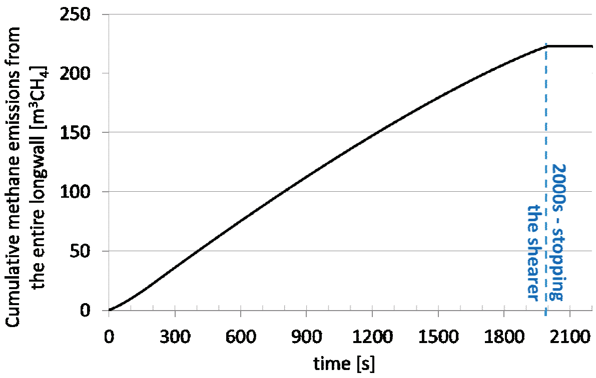


Fig. 18. Cumulative methane emission from the entire longwall as a function of time – the same direction of the shearer and conveyor – temperatures above 20 °C

the sorption capacity change with an increase in the temperature. The parameters being analysed at temperatures above 20 °C will amount to approximately: $D_e = 8 \cdot 10^{-9}$ cm^2/s, A = 2 m^3 CH$_4$/Mg. Thus, graphs will change significantly (Figs. 14–19).

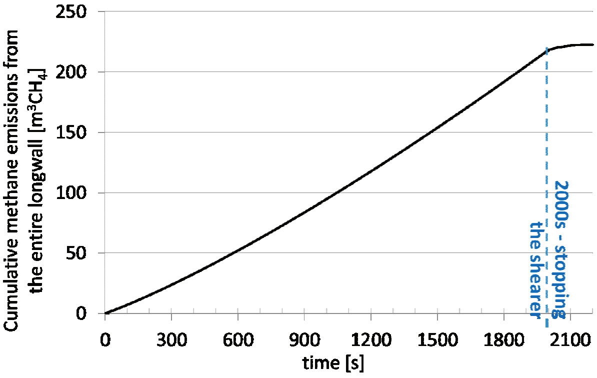


Fig. 19. Cumulative methane emission from the entire longwall as a function of time – opposite direction of the shearer and conveyor – temperatures above 20 °C

The increase in the total methane emission from the longwall seems to be the most significant. As shown in this study, it is particularly strongly related to the value of the diffusion coefficient. The value of the sorption capacity is also important (the difference between the methane content and the sorption capacity is proportionate to the amplitude of solution (2) in Crank's model). In the being analysed, the increase in the depth of the deposit, which results in an increase in temperature by 20°C caused an increase in total methane emission from the longwall for a single cycle of the shearer operation from 156 m^3 CH$_4$ to 233 m^3 CH$_4$, which amounts to 49%.

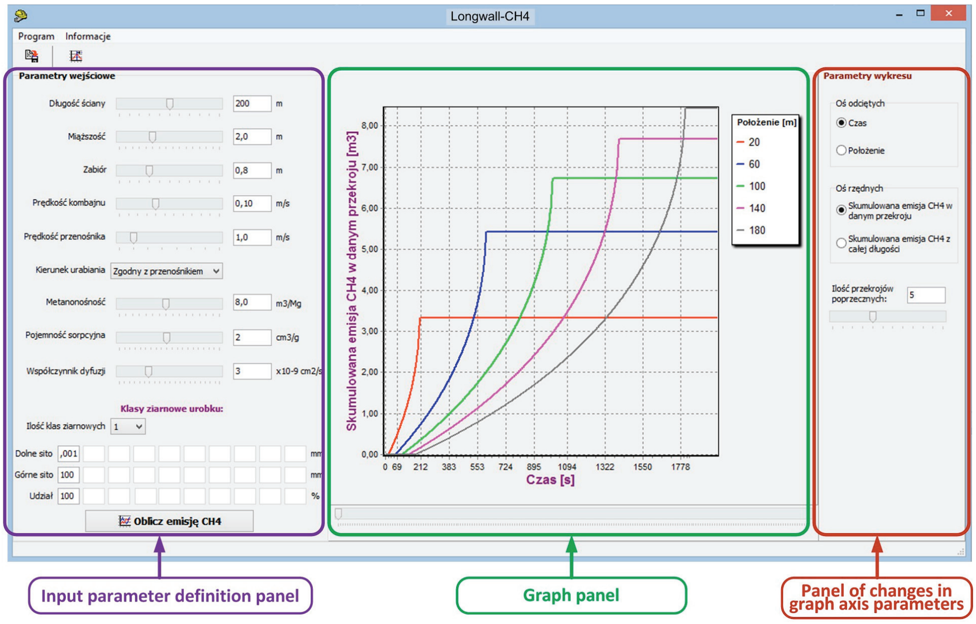
3. DESCRIPTION OF FUNCTIONALITY OF THE "LONGWALL–CH$_4$" SOFTWARE

The "Longwall–CH4" computer program, which simulates methane emission from the coal spoil from a hard coal mine, was created in Codegear C++ Builder 2009. Codegear C++ Builder is an RAD (Rapid Application Development) tool for creating applications in the C++ language, which allows, among other things, building programs operating in various systems (including Windows, Linux, etc.). The "Longwall–CH4" software is intended for the Windows environment.

The main window of the "Longwall–CH4" is divided into three operational panels (Fig. 20):

– The input parameter definition panel;
– Graph panel, which presents the results of calculations of CH$_4$ emission for defined input parameters;
– Panel of changes in graph axis parameters – makes it possible to change the presentation of results on the graph.

Apart from the possibility of changing the parameters for calculating CH$_4$ emission from the longwall and the possibility of automated presentation of calculated model data on the graph, the program also makes it possible to save calculated results in a text file.



Długość ściany 200 m
Miąższość 2,0 m
Zabiór 0,8 m
Prędkość kombajnu 0,10 m/s
Prędkość przenośnika 1,0 m/s
Kierunek urabiania Zgodny z przenośnikiem
Metanonośność 8,0 m3/Mg
Pojemność sorpcyjna 2 cm3/g
Współczynnik dyfuzji 3 x10-9 cm2/s
Ilość klas ziarnowych 1
Dolne sito ,001 mm
Górne sito 100 mm
Udział 100 %

Oś odciętych
● Czas
○ Położenie

Oś rzędnych
● Skumulowana emisja CH4 w danym przekroju
○ Skumulowana emisja CH4 z całej długości

Ilość przekrojów poprzecznych: 5

Fig. 20. The main window of the "Longwall–CH4" software

4. SUMMARY

An IT package has been prepared on the basis of a unipore model, which makes it possible to analyse methane emission from spoil during longwall exploitation. The grain size distribution curve of the spoil collected from the coal mine was used. Detailed analysis of methane emission was performed according to the time and position in the working area. The share of methane emission from individual grain classes was analysed, taking into account both the kinetics of emission and grain size distribution. The share of the lowest classes predominates, in particular below 0.1 mm, despite the fact that the mass share does not exceed 5%. Temporal and spatial changes in emission are consistent with the authors' intuition. For the analysed parameters of the coal-methane system, working area geometry and technological parameters, the cumulative quantity of methane from the entire working area exceeds 156 m^3 CH_4. This value increases sharply together with an increase in the initial rock temperature.

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