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Forecasting the distribution of methane concentration levels in mine headings by means of model-based tests and in-situ measurements

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The methane hazard is one of the most dangerous phenomena in hard coal mining. In a certain range of concentrations, methane is flammable and explosive. Therefore, in order to maintain the continuity of the production process and the safety of work for the crew, various measures are taken to prevent these concentration levels from being exceeded. A significant role in this process is played by the forecasting of methane concentrations in mine headings. This very problem has been the focus of the present article. Based on discrete measurements of methane concentration in mine headings and ventilation parameters, the distribution of methane concentration levels in these headings was forecasted. This process was performed on the basis of model-based tests using the Computational Fluid Dynamics (CFD). The methodology adopted was used to develop a structural model of the region under analysis, for which boundary conditions were adopted on the basis of the measurements results in real-world conditions. The analyses conducted helped to specify the distributions of methane concentrations in the region at hand and determine the anticipated future values of these concentrations. The results obtained from model-based tests were compared with the results of the measurements in real-world conditions. The methodology using the CFD and the results of the tests offer extensive possibilities of their application for effective diagnosis and forecasting of the methane hazard in mine headings.

Key words: CFD, forecasting the distribution of methane, mining heading, in-situ measurements, model tests

1. Introduction

Underground mining exploitation is amongst one of the most dangerous production processes. This results from the changeability of the natural phenomena occurring in the exploited areas. Despite the high dynamics and unpredictability of these phenomena, it is necessary, whenever possible, to undertake actions in

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order to limit the possibilities of their occurrence or minimise their consequences once they have already occurred. This purpose is also served by all the activities aimed at forecasting potential critical states in terms of the hazards present. In the case of hard coal mining, one of the most dangerous phenomena is the methane hazard [1, 2, 4, 7–9, 15, 16]. It is due to the fact that the process of coal exploitation generates methane, which is flammable and explosive in a certain range of concentrations. The occurrence of such events leads to extremely negative consequences and poses a serious threat to the working crew. For this reason, in the case where mining exploitation is performed in seams vulnerable to methane emissions, it is necessary to take measures in order to minimise the potential for its combustion and explosion. It is therefore reasonable to carry out works to assess the occurrence of critical concentrations of this gas. A significant role in this process is played by forecasting methane concentrations in the exploited area, i.e. in places that are most vulnerable to critical methane concentrations.

The efficiency of forecasting activities depends on the forecasting methodology in use, the conditions in which the exploitation takes place and the ventilation system applied. Of particular importance in this case is the amount of methane that can be emitted into the working area of mine headings as well as its concentration levels when mixed with air. This status is assessed by the following methods: empirical, analytical, numerical (simulation), short-term (pseudo-real time) forecasting and hybrid, as computer-based systems for supporting control over the methane hazard (working in real time and cooperating with the monitoring devices of the mine's dispatcher system). These methods make it possible to determine the anticipated amount of methane than can be emitted into the headings. This information makes it possible to select adequate preventive measures in order to reduce the concentration levels of this gas in a mine heading and, consequently, minimise the methane hazard.

The methods currently used in this regard are characterised by highly diverse accuracy and do not fully work in practice. In the majority of cases, the potential values of methane concentration levels are determined with a rough approximation based on exploitation forecasts, most commonly in one or several points of the extraction area [5, 6]. Recently, there have also been works on the application of intelligent systems for forecasting this hazard on the basis of automatic systems registering ventilation parameters in the headings at risk. The preliminary results of these tests are quite optimistic. However, despite their numerous advantages, these methods most commonly specify a given hazard only in a few selected points of the headings [4]. At the same time, some of them are based on the assumed exploitation plans, which not always correspond to the reality. These methods are not capable of determining methane concentration values at the points where no sensors are installed.

For this reason, the Authors of the paper decided to develop a methodology for forecasting the methane hazard in mine headings based on numerical modelling combined with the measurement results of ventilation parameters. Numerical methods are currently being increasingly used as research tools in numerous areas of science, including variant analyses of the processes related to gas distributions in mine headings as well as in analyses of emergency states [1, 2, 8, 9, 14–16]. The solution proposed in the paper allows for determining the concentration distribution for methane and other mining gases in any area under exploitation. At the same time, these parameters can be determined in any given point of this area. An essential element of the methodology developed is the fact that it is based on real-world measurements of the values of ventilation parameters in the mine. These values are used as boundary conditions for the construction of the numerical model. This is because the parameters of air, including methane concentration levels, in mine headings are controlled by a system of automatic gasometry sensors as well as by manual measurements. The results of these measurements, performed on a real-world object, provide data that are used in model-based tests. They also allow for verification and interpretation of the results obtained from these tests.

The modern gasometric systems used in hard coal mines register data with a different frequency. In practice, however, most commonly the data are registered at the frequency of 1 Hz. As a result, these systems provide large amounts of data about phenomena occurring in the ventilation network of a mine. Taking into account the number of sensors located within the area of a single mine heading under exploitation, this amount can reach approximately 0.4 million records per day. At present, in the majority of cases, the results of these measurements are used only for the ongoing assessment of the ventilation risk. In the methodology proposed by the Authors, their task will also include verification of the results obtained from model-based tests.

In the methodology developed, the data from the gasometric systems of a mine provide the basis for the constructed numerical model that defines the ventilation processes occurring in the region under analysis. The accuracy of the results obtained is, to a large extent, dependent on the complexity of the model developed, which – along with the acquisition of new data – may be quite freely extended. This is because the Computational Fluid Dynamics (CFD) technique, when applied in forecasting, provides extensive possibilities for using structural modelling to analyse ventilation states. At the same time, it allows for implementing new tools for ventilation hazard forecasting, which – in the Authors' opinion – may be successfully used for this purpose. This is because structural modelling by means of the CFD should supplement, and in certain cases replace, the methods currently in use.

In order to check the effectiveness of the concept developed, the Authors conducted tests for the selected area of mining exploitation. Direct measurement results of the ventilation parameters in in situ conditions led to the development of a numerical model of the region at hand and to its analysis. The results obtained were compared with the measurement results, and satisfactory correlations were obtained.

The paper discusses the manner of obtaining data, describes the numerical model developed and presents the results obtained. It also presents the possibilities of determining selected ventilation parameters and the manner of their presentation thanks to the application of numerical tools. The Authors hope that the results presented will find practical applications in mining, thus improving the working safety and effectiveness of mining production.

2. Exploration of data from the mine's gasometric system for numerical tests

The numerical tests were performed using the data registered by the gasometric system of the mine. This system consists of the facility section and the dispatcher stations. The former is made up of sensors located in underground headings and stations acting as data concentrators and actuating systems. The latter, on the other hand, include systems of data transmission and power supply to underground equipment, thereby being an intermediary element for the computer-based systems of dispatcher supervision. The databases which collect the physical (e.g. speed, pressure) and chemical (e.g. methane concentration) parameters of the air stream flowing through the mine headings, coming from the gasometric system, contain data in a compressed form. These data are transferred to the system at time intervals resulting from the signal sampling frequency (from 1 second to a dozen or so seconds) and include only those items in which there was a change in the sensor readings with a time stamp [3].

The mine's gasometric system consists of automatic methanometres, anemometres, barometric pressure metres, as well as sensors of carbon monoxide, oxygen, humidity and temperature.

Automatic methanometres register methane concentrations with the resolution of 0.1 CH_4, anemometres – with the resolution of up to 0.1 m/s, and the barometric pressure metres – 1 hPa. These resolutions are sometimes too low and do not fully reflect the nature of the changing air parameters. For this reason, in the event of using these data for forecasting e.g. the methane hazard or for verification and validation of the numerical model, it is necessary for them to be aligned (smoothed). This smoothing can be performed by various methods.

In the case at hand, the time courses of the changing methane concentration values and of the airstream speed were smoothed by means of the Holt's method, which is one of the exponential smoothing techniques. This method involves smoothing of the time series by means of a moving average. The Holt's model is described by means of the following equations [11]:

$$F_t = \alpha x_t + (1-\alpha)(F_{t-1} + S_{t-1}), \tag{1}$$

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$$S_t = \beta\,(F_t - F_{t-1}) + (1-\beta)S_{t-1}\,, \tag{2}$$

where: $t = 2, 3 \ldots, n-1$; F_t – smoothed value of the time series; S_t – smoothed value of the trend gain (growth) per moment t; α, β – smoothing parameters of the model, $\alpha, \beta \in [0, 1]$.

The smoothing parameters are selected based on the criterion of the smallest average error from the expired forecasts [11]:

$$s^* = \sqrt{\frac{1}{n}\sum_{t-1}^{n}\Big(y_t - y_t^*(\alpha,\beta)\Big)^2}\,. \tag{3}$$

An example of smoothed data coming from an automatic methanometre and a stationary anemometre located in the heading that discharges the air from the longwall (airway), using the Holt's method, has been presented in Figs. 1 and 2.

a) b)

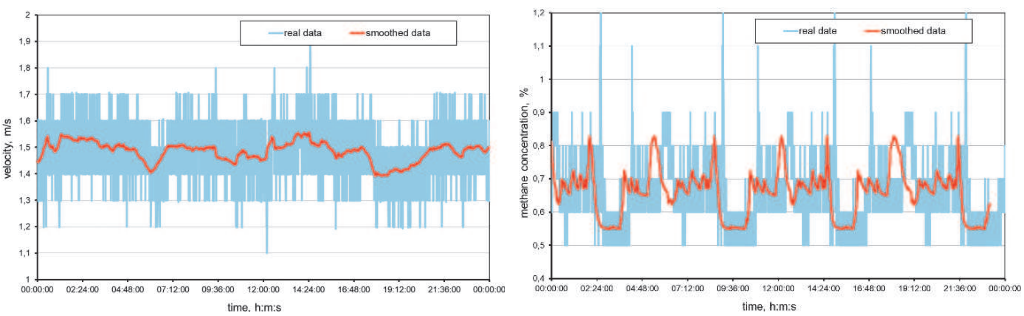

Figure 1: Sample smoothing of the time course of the air speed at the outlet from the longwall (a) and the time course of methane concentration (in the airway 10 m from the longwall outlet) (b)

In underground automatic gasometry systems, the interferences caused by air fluctuations should be eliminated as insignificant from the perspective of permanent changes in the mine's ventilation status. Smoothing the signal by means of the Holt's method makes it possible to use more reliable data for further forecasting analyses.

3. Description of the numerical method

The flow of air and methane mixture in the longwall was analysed by means of the Finite Volume Method (FVM). This method involves discretisation (in a physical space) of the computational domain (the spatial flow area) into a finite number of non-overlapping control volumes. A control volume may be created, depending on the research tool applied, inside the volume of the fluid element or around the volume element node.

In each control volume of the computational domain, there is integration of the basic equations describing the flow of fluid, based on the principles of mass and momentum conservation.

The general form of the transport equation for each control volume written down in an integrated form is as follows [10, 12]:

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho\phi\,\mathrm{d}V + \oint_A \rho\phi v\,\mathrm{d}A = \oint_A \Gamma \operatorname{grad} p\phi\,\mathrm{d}A + \int_V S_\phi\,\mathrm{d}V, \tag{4}$$

where: ϕ – scalar value; Γ – diffusion coefficient, cm^2/s; S_ϕ – volumetric source of the scalar value ϕ; V – control volume of the calculation area, m^3; A – surface of the control area, m^2.

The transport equation (4) represents the form of the scalar conservation equation ϕ for a finite control volume built around node *0*, with the f number of its limiting surfaces $d\mathbf{A}$.

As a result of solving the transport equation, one obtains discrete equations that fulfil the flow conservation laws within each control volume.

In the case of simulation based on a spatial model (3D model), a complete system of 12 equations is solved, consisting of the equation of mass and momentum conservation (in the directions: x, y, z), energy conservation, k, ε, as well as equations of chemical substances conservation (methane, oxygen, nitrogen, carbon dioxide, carbon monoxide).

An algorithm based on the formulation of equations for pressure was used to solve this set of equations. This method searches for a solution to the momentum equation in three directions, obtaining an approximate velocity field, and in the next step it introduces correction of pressures in order to fulfil the equation of mass conservation. Upon implementing corrections to the pressure and momentum equations, additional balance equations are calculated (e.g. energy conservation equation, transport equation for chemical substances, k, ε). While calculating the variable field values, determined for the centre of the control volume, these values were interpolated from the neighbouring cells and the subsequent ones (second-level interpolation sequence). The calculations are performed until the condition for convergence has been obtained, defined on the basis of the remainder value that is the inconsistency between the sides of the equation (5):

$$a_{P\phi P} = \sum_{nb} a_{nb}\phi_{nb} + b, \tag{5}$$

where: a_P – central value coefficient, a_{nb} – coefficient of influence on the neighbouring values, b – share value of the boundary condition.

The algorithm for seeking a solution for the Finite Volume Method (FVM) has been presented in Fig. 2 [13].

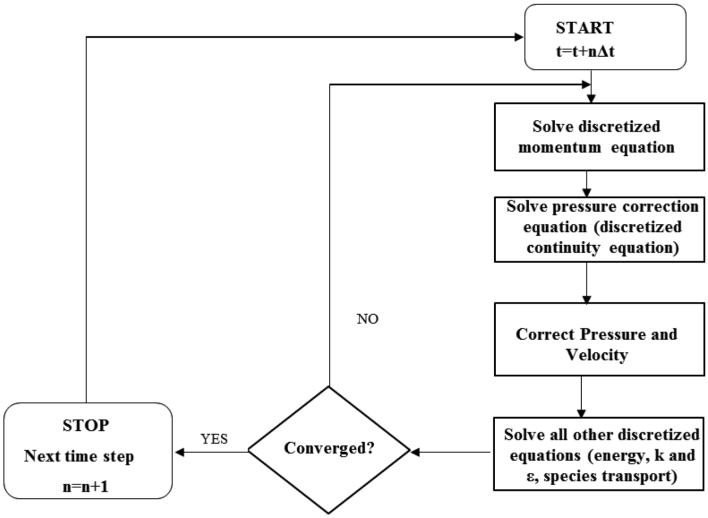

Figure 2: The algorithm for seeking a solution for the Finite Volume Method (FVM)

4. The numerical model of the longwall region

The "X" longwall in the "W" seam was entirely covered by the automatic gasometry system (methanometric protections and anemometres). The distribution of sensors for measuring air parameters in the region of the longwall examined has been presented in Fig. 3. The designations of the sensors are simultaneously designations of the measurement points.

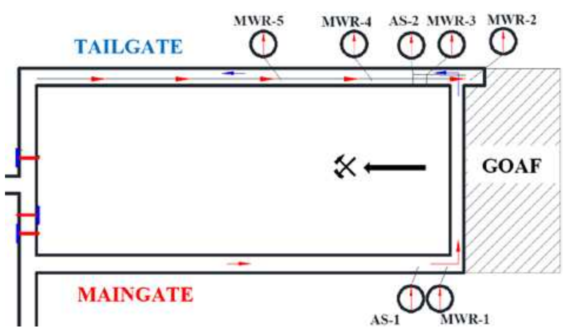

Figure 3: The distribution of sensors for measuring air parameters in the region of the longwall examined

Based on the geometric data of the real-world longwall, longwall galleries and caving goaves of this longwall, its three-dimensional geometric model was created as the first stage of model-based tests (Fig. 4). The geometric parameters of the system of headings at hand and the ventilation parameters of the air flowing through those headings have been summarised in Table 1.

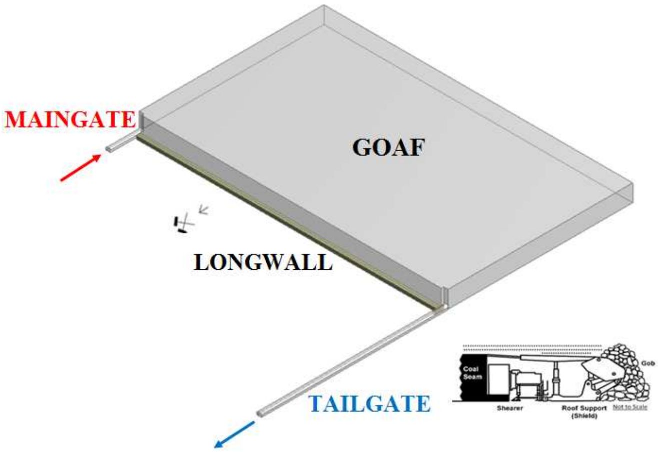

Figure 4: The geometric model of the region under examination

Table 1: The geometric parameters of the system of headings and the ventilation parameters of the air

Air flow supplied to the longwall (maingate), m^3/min	1000.0
Air flow supplied auxiliary lute (tailgate), m^3/min	400.0
Absolute methane content, m^3 CH_4/min	11.36
Height of the longwall, m	2.2
Length of the longwall, m	216.0
Width of the longwall, m	4.54
The width of the sidewalks longwall, m	3.8
The height of the sidewalks longwall, m	5.5

The next stage of the analysis consisted in discretisation of the geometrical model into a finite number of non-overlapping control volumes. A grid consisting of over 33 million elements (control volume) was used for this purpose.

The case at hand was analysed in isothermal conditions, with the assumption of a compound flow (mixture of air and methane), as is the case in real-world

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conditions. The boundary conditions necessary for the performance of numerical calculations were adopted on the basis of real-world measurements of the physical and chemical parameters of the air stream supplied to the longwall as well as on the basis of the methane bearing capacity of the longwall, with account being taken of data smoothing by means of the Holt's method.

5. Results and discussion

The calculations served as the basis for determining the forecasted distributions of methane concentration levels and the distributions of the air stream speed in the intersection area between the longwall and the tailgate (airway) for different calculation times.

Figure 5 presents the distributions of methane concentration levels in the cross-section of the tailgate (airway) at a distance of 6.0 metres from the outlet from the longwall. This place has been marked in Fig. 3 as the MWR-3 point. Further distributions were determined for the following analysis (forecasting) times: a – for 15 333 seconds (4:15:33); b – for 42 637 seconds (11:50:37); c – for 75 189 seconds (20:53:09). Figure 6, on the other hand, shows the distributions of

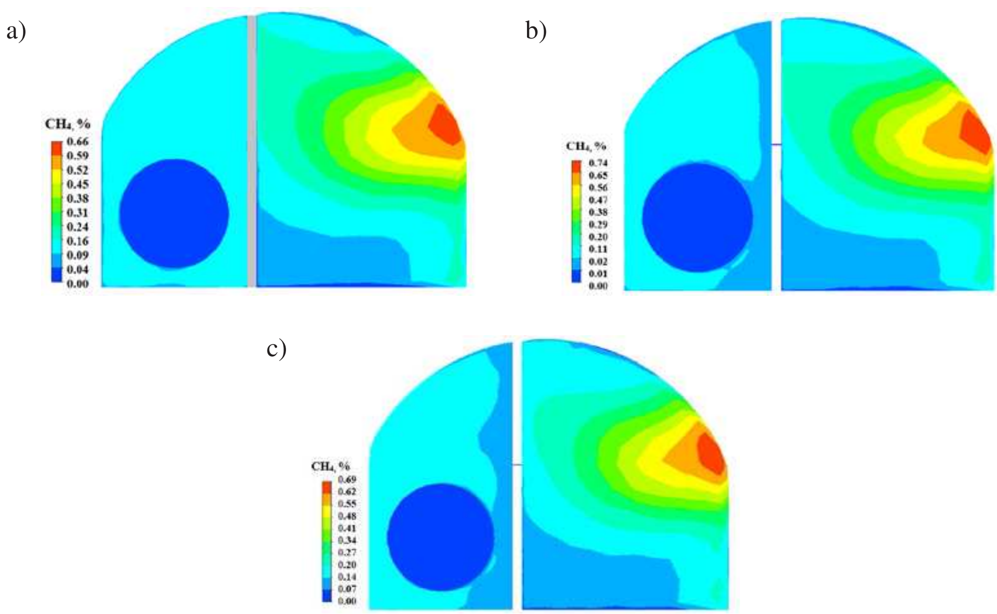

Figure 5: The distributions of methane concentration levels in the cross-section of the tailgate (airway) at a distance of 6.0 metres from the outlet from the longwall for selected forecasting times: a) for 15 333 seconds (4:15:33), b) for 42 637 seconds (11:50:37), c) for 75 189 seconds (20:53:09)

speed for the same calculation times in the installation site of the sensor-stationary anemometer (7 m from the outlet from the longwall – marked as point AS-2 in Fig. 3).

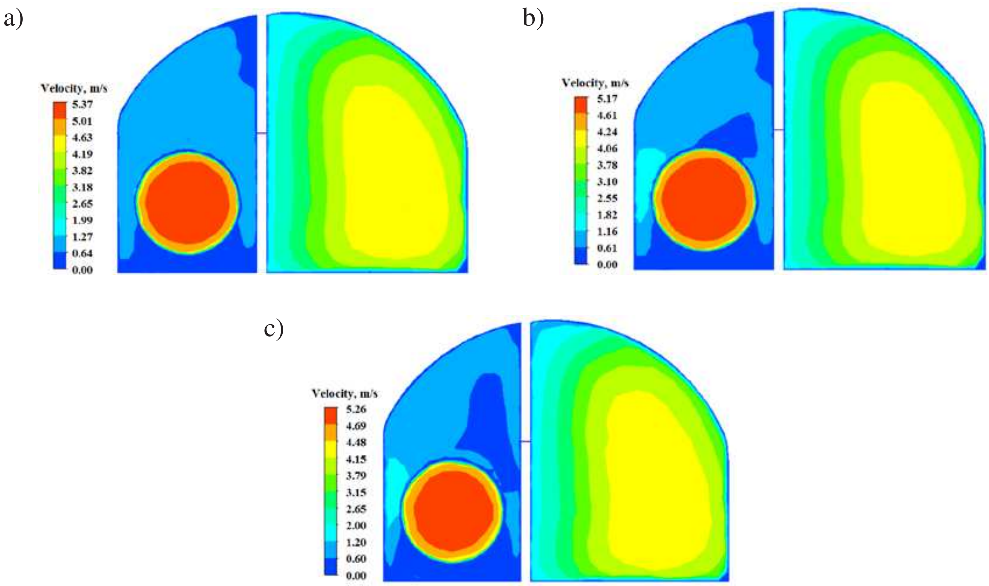

Figure 6: The distribution of air stream speed in the cross-section of the airway at a distance of 7.0 metres from the outlet from the longwall for selected analysis times: a) for 15 333 seconds (4:15:33), b) for 42 637 seconds (11:50:37), c) for 75 189 seconds (20:53:09)

In order to verify the quality of the results obtained, they were compared with the values measured for a single day. Figures 7, 8 compare the methane concentration levels and the air speed in the measurement points for the smoothed data and the results from model-based tests.

Analysing the results obtained, it can be concluded that the results from model-based tests show great convergence with the measurement results.

Model-based tests also make it possible to determine a series of additional parameters and their distributions. These distributions can be determined for any instant of the forecast and for any point of the area analysed. For instance, Fig. 9 presents isolines of methane concentration amounting to 0.65% for selected analysis times: a – 15 333 seconds 4:15:33), b – 42 637 seconds (11:50:37), c – 75 189 seconds (20:53:09).

The results obtained served as the basis for comparing the values of average methane concentration levels and air flow speed, as registered by the sensors of the automatic gasometry system, with those obtained through model-based tests (Table 2).

Figure 7: Comparison of methane concentration values obtained from measurements (smoothed data) and model-based tests in the MWR-3 measurement point

Figure 8: Comparison of the air speed for the smoothed (measurement) data and the results from model-based tests in the AS-2 measurement point

The data summarized in Table 2 demonstrate that results obtained from model-based tests are close to the measurement values registered by the automatic gasometry sensors. The highest value of the relative error amounted to approx. 7%. This concerned the difference between the average speed at the inlet into the longwall, as registered by the AS-2 sensor, and the average value obtained in the

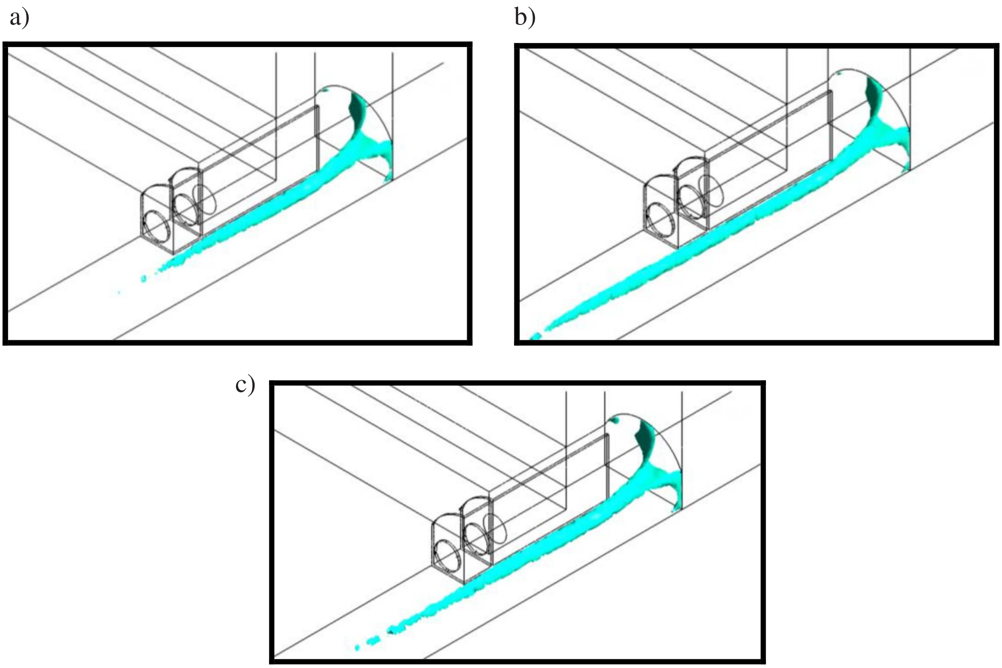

Figure 9: Isolines of methane concentration with the value of 0.65% for selected analysis times: a) for 15 333 seconds (4:15:33), b) for 42 637 seconds (11:50:37), c) for 75 189 seconds (20:53:09)

Table 2: Comparison of the measurement results with the results of model-based tests.

Sensor/Measurement point	Values measures in underground conditions	Results of model-based tests	Relative error %
MWR-1, CH_4%	0.153	0.141	7.843
MWR-2, CH_4%	0.758	0.785	3.562
MWR-3, CH_4%	0.752	0.771	2.527
MWR-4, CH_4%	0.718	0.706	1.671
MWR-5, CH_4%	0.663	0.621	6.335
AS-2, v, m/s	1.481	1.496	1.013
AS-1, v, m/s	1.027	1.100	7.108

simulation. This error is probably due to the fact that the section of the maingate (a gallery along with air is supplied to the longwall) in the geometric model was not sufficient to compensate for the air speed at the inlet section. In other cases, the differences recorded are very small.

6. Conclusions

The use of numerical methods for analysing ventilation phenomena in mines is becoming increasingly popular. It is therefore reasonable to apply this method also to the forecasting of phenomena related to ventilation hazards. A crucial role in this process is played by the reliability of the results obtained. Besides proper development of the model itself, it is therefore also necessary to make use of objective measurement data. In this regard, the paper made use of the performance results of the automatic systems for registering ventilation parameters, which guarantees their reliability and independence from a number of various factors. This is of particularly critical importance in the case of forecasting the methane hazard. This is because wrong results in this area may have extremely negative consequences.

Analysing the methodology developed and the results obtained, one can conclude that model-based tests can be successfully used in forecasting the physical and chemical parameters of the ventilation network in a mine. The only limitations in using this methodology may be the lack of access to reliable measurement data and the computational capacity.

In the case at hand, spatial numerical modelling was used to precisely represent the geometry of the region under analysis. The results obtained unequivocally indicate the places and times in which it is likely for dangerous methane concentrations to occur. It is also possible to trace the distribution course of methane and other gases in the entire area under analysis. The reliability of the forecast, on the other hand, can be easily verified in selected points, e.g. by examining the deviation of the forecast from the real value (the ex post method). It is therefore reasonable to state that forecasting by means of numerical modelling offers extensive possibilities and its range far exceeds that of the other methods used for this purpose.

The results obtained indicate that the place at the highest risk of dangerous methane concentrations for the system under analysis is the intersection area between the longwall and the maingate. In practice, this information should result in this region being placed under special control, along with the installation of additional measurement sensors. It is also important to note the universal nature of the model developed. A well-developed and verified model can be used for multivariate analyses and hazard forecasting for different variants of methane emission and ventilation parameters of the supplied air stream.

The results obtained clearly prove that the application of numerical methods in combination with the results of real-world tests can be successfully used for variant analyses of the processes related to the ventilation of underground mine headings as well as for analyses of emergency states. These activities should also effectively support the forecasting of ventilation hazards.

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