# Computer simulation of air and methane flow following an outburst in transport gallery D-6, bed 409/4

by W. Dziurzyński*, J. Krawczyk*, and T. Pałka*

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## Synopsis

This article outlines the results of a computer simulation reproducing the transport of a mixture of air and methane following the outburst on 25 November, 2005 in transport gallery D-6, bed 409/4, at the 'Zofiówka' hard coal mine. Based on a mathematical model, numerical method and boundary conditions from the disturbance caused by the outburst, the Ventgraph system of computer simulation programs was adopted for the study. We performed a computer simulation of the influence exerted by the outburst on the propagation of the air and methane mixture, and compared the results of this simulation with those of the actual event as registered by sensors of the mine monitoring system. A validation of the model allowed us to present temporal changes in the concentration of methane and air along flow routes.


Keywords: mine ventilation, outburst of methane, numerical simulation, monitoring system.

## Introduction

Increasing the depth at which mining operations are performed is accompanied by a sizeable increase in the saturation of coal beds with methane, resulting in an intensified release of methane to headings[1]. Outbursts of methane and coal continue to be a significant hazard in mining worldwide[8,10,11,12]. Over the past 5 years, the increased risk of methane outbursts in Polish mines has resulted in two such events[7,8]. Outbursts of coal and methane constitute a serious and incompletely identified hazard, which not only threatens the safety and lives of mining teams, but also has far-reaching economic effects. In Poland, interest in the problem of outbursts was rekindled following outbursts in mines owned by the Jastrzębie Coal Company S.A.

On 25 November, 2005, an outburst of coal connected with the influx of a considerable quantity of methane occurred in transport gallery D-6, bed 409/4 of the 'Zofiówka' hard coal mine. Rapid discharge of a mixture of crushed rock and methane caused substantial damage in the first few minutes of the initial phase, limited to one gallery[14]. A longer term effect was caused by the flow of a mixture of air and methane along ventilation routes. In many places, concentrations reached the explosive range. This phase lasted a few hours. From the point of view of mine ventilation, the outburst resulted in a potentially catastrophic situation, hazardous to the whole network. Such phenomena have aroused the interest of ventilation services for a number of reasons; the most important include the following:

- the sequence and timing of propagation of released methane to headings or parts of the mine following the outburst
- the designation of zones threatened with an outburst at specific points
- methods of degassing headings following an outburst
- the stability of the ventilation system following an outburst
- the influence of methane as an outburst gas on the nature of the disturbance.

Calculations of the propagation of air in the mine ventilation network form a significant control element of the mine ventilation system. In most cases, and in particular for steady state, these calculations are fairly simple. However, determining air propagation for conditions of a mine emergency or catastrophe is a significant calculation problem due to the non-stationary nature of the events. For this reason, determining the influence of a ventilation disturbance, such as an outburst, on the propagation of air and methane in a network of headings constitutes a scientific issue of considerable importance. We propose to resolve this issue through the use of a simulation applied to the behaviour of systems such as a mine ventilation system, which is made up of headings (branches), nodes and ventilation equipment. Having a model of the

* *Strata Mechanics Research Institute, Polish Academy of Sciences, Cracow, Poland.*

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system is an important element of the research on mine ventilation networks based on simulation. For numerical methods, this is usually the mathematical model that takes into consideration with sufficient precision the phenomena occurring in the actual system with considerable influence on the solution to the problem. Initial conditions describe the state of the flow in the ventilation network until the moment of outburst. The boundary conditions depict the influence of the surrounding environment (virgin coal, rock, influx of methane) on the functioning of the ventilation system.

In this paper, we present the results of a simulation of the propagation of an air and methane mixture in a ventilation network following an outburst of coal and methane. In the initial phase, we neglect direct effects of rock and gas mass characteristics.

Thanks to the continuous operation of the monitoring system in the Zofiówka mine and the registration of methane concentration changes by sensors, it is possible to compare these actual numbers with the results of the simulation. This enables a validation of the mathematical model applied in the Ventgraph computer system and the computer database of the network of headings at the Zofiówka hard coal mine. This research will be used as the basis for assessing the methane hazard that followed the outburst in transport gallery D-6 of bed 409/4.

## Mathematical model, numerical methods and initial boundary conditions

Applying the most sophisticated mathematical models is inefficient for simulating flow in large ventilation networks. Simplified descriptions, based on a one-dimensional flow approximation in which some phenomena are neglected, such as pressure wave propagation and diffusion of methane, save a lot of computational time, which is crucial for frequent multivariate case studies.

We selected a particular solution based on the work of Trutwin, Tracz and Dziurzynski[2], which compares mathematical models of the transport of outburst gases in a network of ventilation workings. The simplest model, named quasi-static, can reproduce propagation of outburst gases with sufficient accuracy. This model has been applied in the Ventgraph software[6]. For the fire module of this package, the quasi-static model has been extended. Additional features enable prediction of phenomena caused by a fire in a mine and inflow of gases related to both the fire itself and to other gases, such as oxygen, nitrogen and methane. Hereafter, we present the quasi-static model used in Ventgraph, except for the model of the fire, description of which may be found in references[4].

### *The flow of the air and gas mixture in the heading*

The flow of the air and gas mixture in the mine heading is described by a system of equations of momentum, continuity and state (see[2,3,5,9,12]). This system combines equations of steady flow of air and admixed gases with unsteady gas transport and energy equations in the way described below. For flow distribution in the network, the response time to changes of boundary conditions, such as quantity of methane inflow, or parameters such as resistance and natural ventilation, is on the order of a minute. The process of admixed gas propagation lasts for hours, justifying the treatment of the phenomena as quasi-static with respect to flows.

The equations of the quasi-static model have the following forms:

- equation of momentum for the stationary state:

$$\frac{\partial p}{\partial s} + g\rho \frac{dz}{ds} + j + j_D \delta\left(s - s_D\right) = h_f \delta\left(s - s_f\right) \qquad [1]$$

- equation of continuity for the stationary state:

$$\frac{\partial\left(v\rho\right)}{\partial s} = 0 \qquad [2]$$

- equation of energy for unsteady state:

$$c_p\left(\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial s}\right) = q_{RO} \qquad [3]$$

- equation of state:

$$p = T\sum_{r=1}^{nr}\rho_r \tilde{R}_r \qquad [4]$$

where: $s$ – designates the spatial coordinate measured along the axis of the heading [m],

and

$s_D$ – coordinate of the point of occurrence of losses (ex. a door D)

$s_f$ – coordinate of the location of fan $f$

$\delta(s - s_D)$, $\delta(s - s_f)$ – Dirac delta functions [1/m]

$z$ – height coordinate, directed upwards [m]

$t$ – time [s]

$p(s,t)$ – absolute pressure [Pa]

$g$ – gravity acceleration [m/s$^2$]

$v(s,t)$ – velocity of flow of the air-methane mixture [m/s]

$\rho = \rho(O_2, N_2, CH_4, GP)$ – density of the mixture of gases [kg/m$^3$]

$\rho_r = \rho_r(s,t)$, $\tilde{R}_r$ – partial density and the gas constant of the $r$ component of the gas mixture [kg/m$^3$], $nr$ – number of components.

where for: $O_2$ – oxygen, r = 1

$N_2$ – nitrogen, r = 2

$CH_4$ – methane, r = 3

GP – components of combustion products, commonly known as fire gases, r = 4.

$C_r(s,t)$ – mass fraction of the $r$ gas component in the mixture, given by the equation:

$$C_r = \frac{\rho_r}{\rho} \qquad [5]$$

there is also a just relation:

$$\sum_{r=1}^{nr} C_r = 1 \qquad [6]$$

$j_D$ – loss of pressure [Pa] at local resistance placed at coordinate $s_D$

$h_f$ – pressure of fan [Pa] placed at coordinate $s_f$

$j = j(s,t)$ – hydraulic gradient [Pa/m], given by the formula:

$$j = \frac{\lambda\rho F}{8A} v\left|v\right| \qquad [7]$$

$\lambda$ – dimensionless resistance coefficient

$F$ – circumference of the heading [m]

$A$ – transverse area of the heading [m$^2$]

$T(s,t)$ – temperature of the mixture of air and fire gases[K]

$q_{RO}$ – quantity of heat exchanged between the flowing mixture of air and fire gases and rocks per unit of time and fluid mass $\left[\frac{J}{skg}\right]$,

$c_p$ – specific heat of the mixture $\left[\frac{J}{kgK}\right]$,

Placing [7] in [1] and following additional conversions, we obtain:

$$\frac{\partial p}{\partial s}+g\rho\frac{dz}{ds}+\frac{1}{\rho^2}\frac{\lambda\rho F}{8A^3}vA\rho|v|A\rho+ j_D\delta(s-s_D)=h_f\delta(s-s_f) \quad [8]$$

When considering an incompressible flow, we adopted $\frac{\partial\rho}{\partial p}=0$; for this reason, the density of the mixture solely depends on the concentration of components of the mixture. To simulate fires, the variation of density with temperature is also considered. If in the equation of state [4] we include the mass concentration $C_r(s,t)$ of the $r$ component as given by [5], we obtain a relationship for $\rho$ – density of a mixture of gases:

$$\rho=\frac{p}{T\sum_{r=1}^{nr}C_r\tilde{R}_r} \quad [9]$$

According to [6] the sum of concentrations equals unity, so one of concentrations, e.g. of oxygen, may be expressed by remaining ones ($C_{o_2}=1-\sum_{r=2}^{nr}C_r$), therefore:

$$\rho=\frac{p}{T\left[\tilde{R}_{o_2}+\left(\tilde{R}_{CH_4}-\tilde{R}_{o_2}\right)C_{CH_4}+\left(\tilde{R}_{N_2}-\tilde{R}_{o_2}\right)C_{N_2}+\left(\tilde{R}_{GP}-\tilde{R}_{o_2}\right)C_{GP}\right]} \quad [10]$$

We have assumed that:

$\tilde{R}_{O_2}$ – oxygen gas constant, $\tilde{R}_{O_2}=259.83$ [J/kgK]

$\tilde{R}_{CH_4}$– methane gas constant, $\tilde{R}_{CH_4}=518.37$ [J/kgK]

$\tilde{R}_{GP}$ – fire gases gas constant, $\tilde{R}_{GP}=287.11$ [J/kgK].

air is a composition of oxygen and nitrogen, so $C_{AIR}=C_{O_2}+C_{N_2}$.

In order to determine changes in the concentration of flowing gases (methane, nitrogen, oxygen) during the flow of the mixture in the heading, we have adopted the following equation of continuity:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho v)}{\partial s}=0 \quad [11]$$

and for the $r$ component of this mixture, e.g., methane,

$$\frac{\partial\rho_r}{\partial t}+\frac{\partial(\rho_r v)}{\partial s}=0 \quad [12]$$

If in Equation [12] we include Equation [11] and Formula [5], then following conversions we obtain the following equation:

$$\frac{\partial C_r}{\partial t}+v\frac{\partial(C_r)}{\partial s}=0 \quad [13]$$

Due to the numerical method employed, we integrate Equation [8] along the length $L_i$ of the $i$th heading. Taking into consideration the equation of Continuity [2], we can write:

$$\int_0^{L_i}\frac{\partial p}{\partial s}ds+\int_0^{L_i}g\rho\frac{dz}{ds}ds+\int_0^{L_i}\frac{\lambda\rho F}{8A^3\rho^2}Q^M\left|Q^M\right|ds+ \int_0^{L_i}j_{D,i}\delta\left(s-s_{D,i}\right)ds=\int_0^{L_i}h_{f,i}\delta\left(s-s_{f,i}\right)ds \quad [14]$$

Introducing average values of density, cross-section and perimeter for each branch, we can formulate Equation [15], which is approximately equivalent to [14]:

$$\left[p_i(L_i)-p_i(0)\right]+\frac{R_i}{\rho_i^2}Q_i^M\left|Q_i^M\right|+g\rho_i \left[z_i(L_i)-z_i(0)\right]+j_{D,i}=h_{f,i} \quad [15]$$

where the following have been adopted:

$\rho_i=\frac{1}{L_i}\int_0^{Li}\rho ds$ – average density

$Q_i^M=v_iA_i\rho_i$ – mass flow quantity of the mixture in the heading [kg/s],

$R_i=\frac{\lambda_i\rho_iF_iL_i}{8A_i^3}$ – aerodynamic resistance of the heading [kg/m[7]].

Taking into consideration mesh equations for the ventilation network and introducing a matrix notation for the network structure, we obtain:

$$\sum_{i=1}^{NB}\alpha_{m,i}\left[\frac{R_i}{\rho_i^2}Q_i^M\left|Q_i^M\right|+g\rho_i\left[z_i(L_i)-z_i(0)\right]+j_{D,i}-h_{F,i}\right]=0 \quad [16]$$

$$m=1,2,\ldots,M,\quad i=1,2,\ldots,NB,$$

where: $\alpha_{m,i}$ – elements of the mesh-branch coincidence matrix

$M=NB-NJ+1$ – number of independent meshes in the ventilation network

$NB$ – number of branches in the ventilation network

$NJ$ – number of nodes of the ventilation network.

A nodal equation also applies to the ventilation network, in the following form:

$$\sum_{r=1}^{nr}\omega_{r,k}+\sum_{i=1}^{NB}\varepsilon_{k,i}Q_i^M=0 \quad [17]$$

where: $k=1,2,..NJ$

$i=1,2,..NB$

$\omega_{r,k}$ – influx of the (pure) $r$th component of gas to the $k$th node [kg/s],

$\varepsilon_{k,i}$ – elements of the node–branch coincidence matrix.

The volume of the methane emission stream $\omega_{r,k}=q_M(t)$ (for $r=3$) flowing in after the outburst exerts a strong influence on changes in the course and quantity of the flow of the mixture and the concentration of methane. In previous works[3] concerning the simulation of air and methane mixture propagation, it was assumed that inflow of methane following an outburst is characterized by three phases:

- the initial phase, during which the outburst builds up to its maximum outburst intensity
- the stabilized outburst phase
- outburst decay.

The above phases are characterized by different time constants and a change in the quantity of inflowing methane. In the event of an outburst, and in particular if the monitoring system registers changes in the concentration of methane, it is possible to recreate its course. Such a simulation is based on defining the inflow of methane as a function $q_M$ $(t)$. Next, a set of data of the methane inflow is created in a time-flow quantity system of co-ordinates, which constitute a variable in the time boundary condition for simulating the outburst.

The equations thus obtained [16], together with mass conservation conditions for nodes [17], comprise a system of algebraic non-linear equations. One of the most effective numerical methods of this system of equations is H. Cross. This system is conjugated with Equation [13] for each branch of the ventilation network through the specific parameters $\rho_r, C_r$ $v$ (density, concentration and speed). Gas transport is much slower than $dv/dt$, which allows the set of equations to decouple. First, we calculate the flow distribution (mass flows in Equations [16]) with the current distribution of temperatures and concentrations fixed, as if the flow were steady. Then, we solve the transport [13] and energy [3] solutions using the explicit characteristics method. A new distribution of temperatures, concentrations and densities gives updated values of resistance and natural ventilation in [16]. This sequence of calculations is repeated at each time step. Combining a series of steady flow solutions with parameters updated according to unsteady transport solutions justifies the 'quasi-steady' feature of this model.

### Simulation of the effects of the methane outburst in transport gallery D- 6, bed 409/4

In order to depict changes in air and methane flow in the ventilation network of the Zofiówka hard coal mine, we performed calculations for the transient caused by a methane outburst in transport gallery D-6, bed 409/4 (Figure 1). The solutions obtained are presented in the form of temporal courses of selected quantities characterizing the state of ventilation following an outburst. The network of headings of the Zofiówka mine has a current computer database in the Ventgraph system format, which constituted the input data for this research.

On 22 November, 2005, at the face of developed transport gallery D-6, bed 409/4, an outburst of methane occurred during operation of the continuous miner. Within the ventilation network of the Zofiówka mine, an automatic methane measuring system registered the concentrations of methane in mine headings following the outburst. These records made it possible to analyse the data, and it was determined that the outburst was characterized by a rapid build-up (80 sec.) to a maximum value $q$ = 12 $m^3/s$, followed by a period of stabilized outburst for 60 s., then decay of the outburst with a time constant of 10 min. The location of the methane concentration sensors around the outburst is presented in Figure 1. Within the area of transport gallery D-6, bed 409/4, an MM 108 sensor is installed; this was used to designate the course of the influx of methane following the outburst.

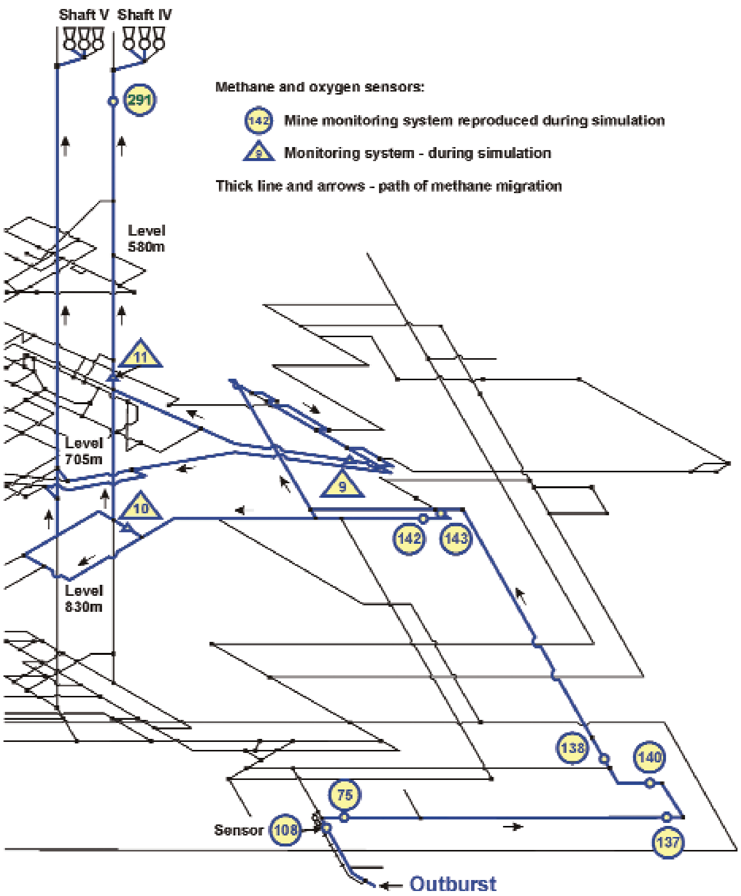


Figure 1—Locations of sensors near section D, bed 409/4

The changes in the concentration of methane for this sensor are presented in Figure 2. These constitute a disturbance in the flow of the air and methane mixture in the ventilation network of the mine, which varies over time.

For the initial conditions thus set, we calculated propagation from the adopted time step at a given moment in time. Following the calculation of the distribution of outburst gas concentration, we determined the distribution of flowing air density, and then the new value of natural ventilation pressure caused by the influx of methane. This constitutes the basis for determining the rate of flow in the next time step. As calculations were performed, results from individual transient states were introduced to sets of results, making it possible to draw diagrams at the locations of methane measurement sensors and other selected headings where methane measurement sensors were not installed. In addition, during the simulation, we also registered changes in the concentration of oxygen, which allowed us to present oxygen deficiency along the path of the air and methane mixture.

### *Development of methane hazard caused by the outburst—computer simulation*

We present diagrams of changes in methane concentration in successive figures, obtained on the basis of automatic methane measurements (dotted light line) and a computer simulation (solid line).

### Conclusions

The computer simulation showed good compatibility with changes in the concentration of methane and courses registered by mine sensors. When analysing the changes on diagrams, we can observe a certain incompatibility in the inclination of curves depicting changes in the concentration of methane obtained from computer calculations, although the amplitudes of changes are comparable. The considerable difference of the simulated and recorded concentration amplitudes seen in Figure 5 may be justified by the relatively close location of this sensor to the outburst site. With the methane incompletely mixed with air, the sensor (routinely placed close to a ceiling) could indicate higher values. The quicker increase in the concentration of methane during the simulation is due to the fact that the diffusion of methane was not taken into consideration in the model. This is visible in particular when comparing changes registered in Shaft IV by sensor MM-291 (Figure 16).

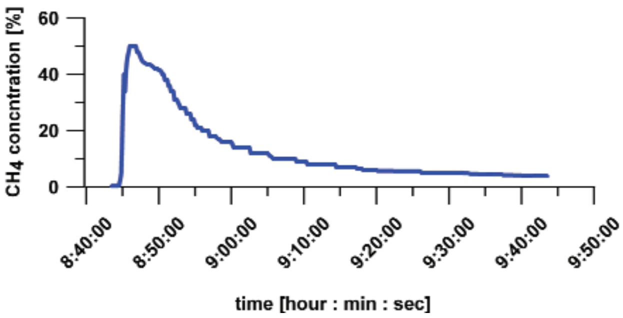


Figure 2—Changes in the concentration of methane, sensor MM-108

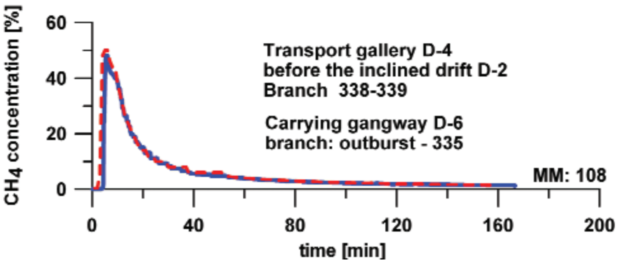


Figure 3—Changes in methane concentration, MM:108 sensor

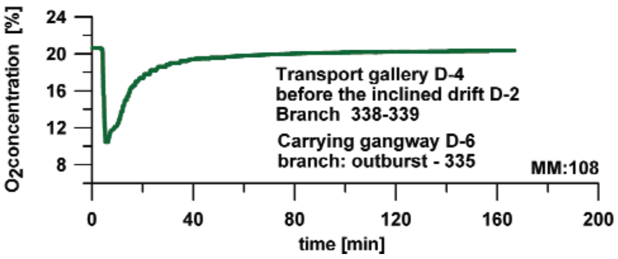


Figure 4—Changes in the concentration of oxygen at sensor next to MM:108

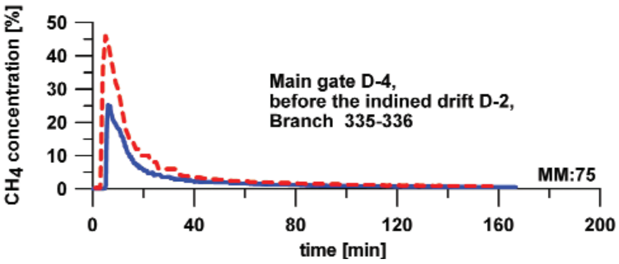


Figure 5—Changes in the concentration of methane, sensor MM:75

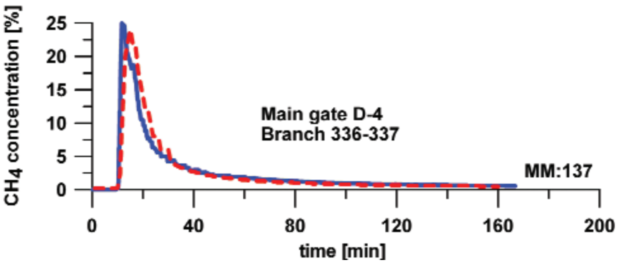


Figure 6—Changes in the concentration of methane, sensor MM:137

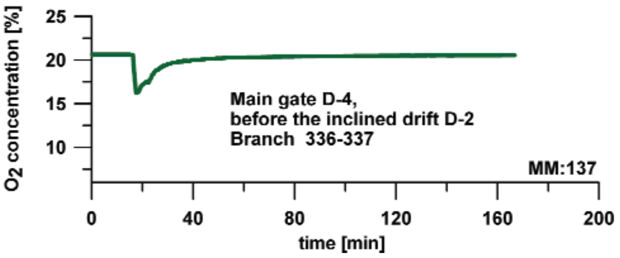


Figure 7—Changes in the concentration of oxygen at sensor next to MM:137



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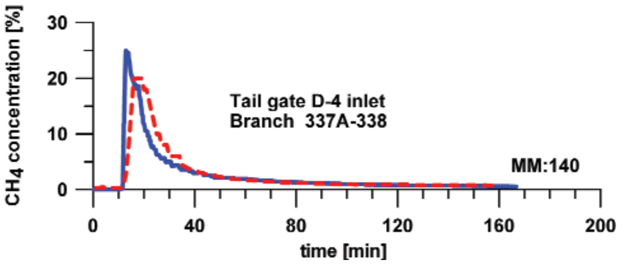


Figure 8—Changes in the concentration of methane, sensor MM:140

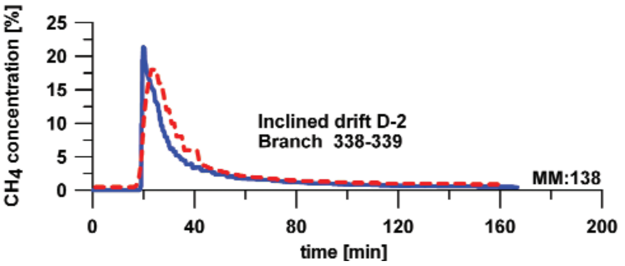


Figure 9—Changes in the concentration of methane, sensor MM:138

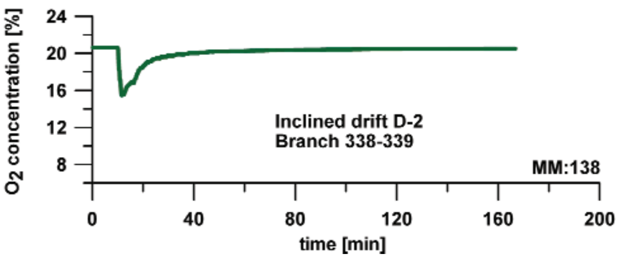


Figure 10—Changes in the concentration of oxygen at sensor next to MM:138

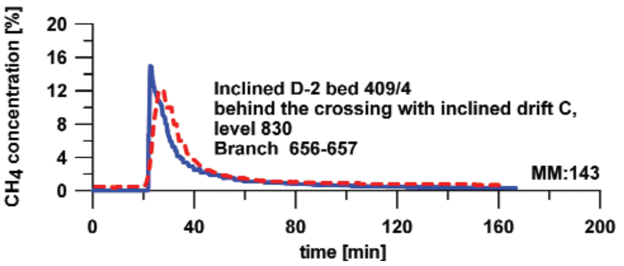


Figure 11—Changes in the concentration of methane, sensor MM:143

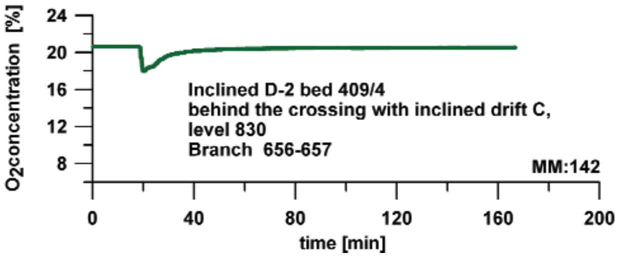


Figure 12—Changes in the concentration of oxygen at sensor next to MM:142

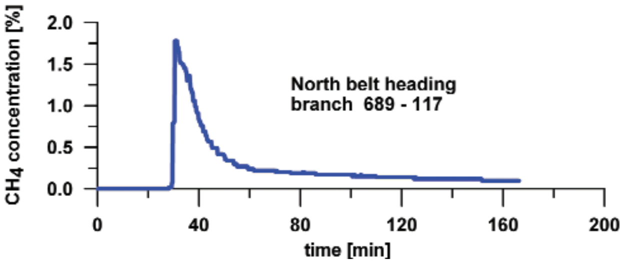


Figure 13—Changes in the concentration of methane, North belt guide, sensor no. 9

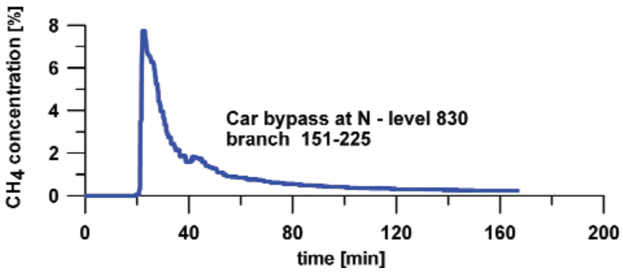


Figure 14—Changes in the concentration of methane, N car bypass, sensor no. 10

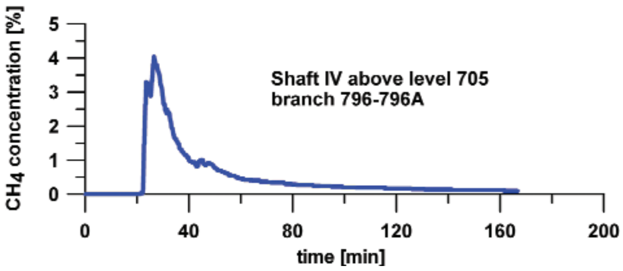


Figure 15—Changes in the concentration of methane, Shaft IV, level 705, sensor no. 11

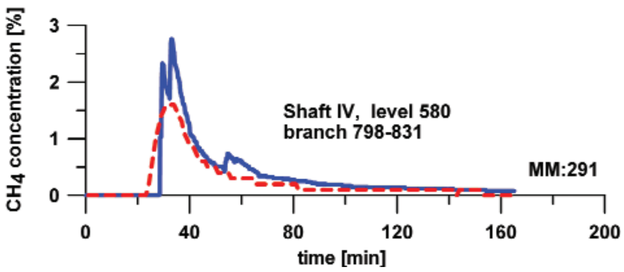


Figure 16—Changes in the concentration of methane, Shaft IV, level 580, sensor MM-291 no. 15

On the basis of the computer simulation, it was possible to observe ventilation routes used to convey outburst gases; we can draw the following conclusions:

➤ The outburst was characterized by rapid build-up (80 seconds) of the influx of methane from the forehead of transport gallery D-6, bed 409/4, to a maximum value of $q$ = 12 m³/s, then by a stabilized outburst for 60 sec.; this was followed by rapid decay of the inflow of methane with a time constant of 10 minutes. Sixteen hours after the start of the outburst, 13360 m$^3$ of pure methane had reached the network of headings, while in the first hour the influx totaled 7750 m$^3$

➤ The simulation was compatible with the observations for both the level and the duration of changes in the concentration of methane

➤ The adopted model corresponds to the actual conditions on the day of the outburst, 22 November, 2006. The above allows us to formulate further conclusions:
  - The simulation allowed us to assess the methane hazard outside the locations of the sensors of the Zofiówka mine monitoring system:
    - headings threatened with flow of methane with a content in excess of 5% $CH_4$ were determined, as well as the duration of this hazard
    - the flow of the air and methane mixture could be characterized by periodic reduction in the oxygen content of the mixture
    - the headings and durations of the 'oxygen' disturbance were determined.

➤ Our analysis of the event shows that it is necessary for mines to maintain up-to-date computer records of the characteristics of the ventilation network. This would make it possible to control the state of ventilation in the event of a hazard, and to perform the appropriate post-incident analysis of the development of the event.

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