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Formation of Methane Hazards During Underground Coal Production in the Longwall Area Ventilated by System Y

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Abstract
The article addresses a critical and timely issue: improving safety in underground coal mining. The primary objective of the paper was to develop a research methodology based on modelling studies to identify and assess the state of methane hazards during mining operations. To achieve this, structural modelling of the physical and chemical phenomena occurring in mining regions was conducted using Computational Fluid Dynamics. The core research was performed using the finite volume method on a real longwall exploitation site ventilated by a Y-system. This approach enabled the determination of methane and oxygen concentration distributions in the mining region and goafs, treated as a porous and permeable medium. Based on these findings, potential fire and/or methane explosion hazard zones were identified in the goaf. The model test results underwent a validation process, comparing them with actual measurements. The determined errors were within an acceptable range, confirming the accuracy of the developed model of the mining region and the phenomena within it. Furthermore, the model was used to predict the locations of zones at risk of fire and/or methane explosion in the goafs, particularly in areas with potentially increased gas emissions. The results clearly demonstrate the significant potential of using model studies to diagnose and forecast methane hazards in underground mining operations. Identifying these potential danger zones allows for the implementation of preventive measures to reduce the likelihood of dangerous incidents.

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1. Introduction

Despite ongoing changes in the structure of energy resources and environmental protection measures, hard coal, classified as a conventional energy resource, continues to play a key role in the global energy mix. For many countries, it is the primary source for the production of electricity and heat (Brodny and Tutak, 2022). It is also the primary raw material for coke production and is widely used in the chemical, pharmaceutical, and many other industries. The wide use of coal and its strategic importance, especially in the current geopolitical reality, has led to an increase in global production (mining). On the other hand, the coal production process itself, particularly the aspects related to underground exploitation, is one of the most dangerous. Its underground extraction in unpredictable conditions leads to the occurrence of several natural hazards that adversely affect both the operation of all kinds of equipment, including, in particular, mining machinery and crew.

One of the most serious hazards present in this process is ventilation hazards, which include methane and heat hazards, among other risks. Of these, methane hazards associated with the emission of methane – an odorless, colorless, and lighter-than-air gas – into mine workings are particularly dangerous. In addition to its very good energy properties, such a methane mixture becomes flammable and explosive at the right concentration and with the availability of oxygen (Palka et al., 2022; Tutak and Brodny, 2017). These characteristics mean that in underground workings, methane poses a huge potential threat to the safety of the crew, the continuity of the mining process, and its efficiency. The reality of this threat is evidenced by statistics, including compilations of events and their consequences – most often of a catastrophic nature – that occurred in Polish and global coal mines, where fires and methane explosions were the causes (Gajdzik et al., 2022; Ray et al., 2022).

In addition to these events, exceeding the permissible concentrations of methane in mine workings also exerts a significant and negative impact on the continuity and efficiency of the mining process. These conditions cause power outages of equipment and machinery, resulting in unscheduled interruptions in their operation (Brodny, 2010; Brodny et al., 2017). Although such interruptions do not pose direct danger to the crew and machinery, they are highly unfavourable for the overall mining production process.

It can therefore be assumed that methane poses a very significant and real threat to the process. Consequently, it is fully justified to carry out research aimed at improving safety in underground mining production. One of the key directions of such efforts is the identification of locations where dangerous concentrations of this gas can occur, both in mine workings and in goafs. Goaf, in particular, is an immensely dangerous and difficult-to-monitor zone where methane can accumulate. From this zone, as a result of the ventilation process, methane can flow into the longwall gallery, further worsening the ventilation conditions in this area. It should also be noted that the methane in the goaf can ignite or explode in the event of an endogenous fire, leading to extremely dangerous combined hazards.

On the other hand, it is clear that the primary cause of fires and/or explosions involving methane is its dangerous concentrations. Therefore, it becomes crucial in the process of combating this danger to identify such locations along with the potential values of these concentrations. Unfortunately, the conditions under which underground mining operations are carried out are not conducive to monitoring methane concentrations throughout the entire working space and goafs. Measurements are conducted in accordance with current regulations at selected points, increasingly often with the aid of automatic methanometry systems. These measurements can be considered nearly continuous, as they are carried out with frequencies as high as 5 Hz. However, the most common measurement frequency is 1 Hz.

Limited monitoring of methane concentrations in mine workings, combined with the practical absence of such monitoring in goafs, results in frequent exceedances of permissible concentrations of this gas, as well as fires and/or explosions in these zones, despite the preventive measures described above. Therefore, it is fully justified to conduct studies aimed at identifying potential sites where such elevated concentrations of methane may occur. Given the extremely harsh environmental conditions and the practical impossibility of conducting measurements in real conditions for technical, economic, and safety reasons, it becomes necessary to employ alternative testing methods.

Model studies based on structural modelling offer a way to determine the distribution of methane concentrations in mine workings and goafs, which are treated as porous, permeable media. In this context, the use of advanced tools for modelling and numerical simulation of physical and chemical phenomena, utilizing the structure of the mining region under study, is fully justified.

One of the most effective approaches for studying such problems is the application of Computational Fluid Dynamics (CFD). This method, designed to investigate flow phenomena in various types of media, enables the modelling and simulation of different states and processes. Consequently, it is fully appropriate to use CFD to study the flow phenomena occurring in mine workings and goafs during the process of underground mining.

The purpose of employing this method is to determine the distributions of methane concentrations in mine workings, specifically in the face zone and goafs. Based on these findings, zones of potentially dangerous methane concentrations, which could lead to the risk of ignition and/or explosion, will be identified. This information should be utilized to develop effective safety procedures aimed at reducing the risk of hazardous methane concentrations. In addition, the research will include an analysis of emergency scenarios involving ventilation conditions, which should lead to a better understanding of the phenomena occurring and improved preparation of ventilation services for potential emergencies. This will help reduce the risk of fires and/or methane explosions, thereby enhancing worker safety and improving the efficiency of the production process. Identifying potential areas of large methane accumulations will also be crucial, as this should enable ventilation services to respond quickly to limit exceedances of permissible concentrations. In turn, this should reduce unplanned interruptions in the operation process caused by such exceedances.

Previous literature on the use of Computational Fluid Dynamics (CFD) in identifying methane hazards has primarily focused on driven dog headings and longwalls ventilated using the U system. In this context, one paper (Wang et al., 2017) presented the results of research utilizing the CFD method to illustrate the spread of methane and its flow in longwalls ventilated by the U system. The results indicated that methane concentration around the shearer loader increases during coal body mining from the maingate to tailgate direction, then decreases when mining in the return direction. Meanwhile, another paper (Mishra et al., 2018) examined methane concentrations at the intersection of the longwall and the tailgate under different geological-mining conditions. However, the study did not account for the goafs, and the CFD model was simplified to include only parts of the longwall and tailgate, represented as a rectangle. Similar research was presented in another paper (Rao et al., 2023) where the authors included goafs in the developed model and additionally determined methane and oxygen concentrations in these goafs, representing a new approach to the subject. Li et al. (2020), using numerical modelling, determined the gas explosion risk in longwall goaf areas. Longwalls ventilated by the U system are also presented in other studies (Zhang et al., 2023) and (Zhao et al., 2023), where methane concentration in the goafs of the studied longwall was determined. Unfortunately, these studies did not include the tailgate, which is crucial in the study of such phenomena.

All of the discussed studies were conducted for longwalls ventilated with the U system. However, there is a lack of research on longwalls ventilated using the Y system, which is also frequently used in practice.

CFD has also been employed to study ventilation phenomena in dog headings. For example, a study (Torano et al., 2009) was conducted to determine methane concentration in a driven dog heading for different ventilation systems. In another paper (Kurnia et al., 2014), the authors examined methane concentration in a driven dog heading for different volumes of methane emitted into the excavation. Another study (Rahimi et al., 2021) presented the effects of uncertainty in gas emissions on airflow parameters and methane concentration during the use of auxiliary ventilation.

When analyzing the cited works, it can be concluded that the CFD method is widely used to study ventilation phenomena in the process of underground mining operations. This is primarily due to the complexity of the ventilation phenomena occurring during these processes and the limited possibility of conducting research in real conditions. Additionally, the method itself, along with programs utilizing the finite volume method, has advanced to a level that allows for the precise representation and study of such phenomena.

This paper presents the research methodology and results of the study on the distribution of methane concentration in the region of underground mining of a longwall ventilated by the Y system, incorporating the goaf as a porous medium. The study was conducted using the Ansys Fluent program, which is based on the finite volume method.

Based on the determined distributions of methane concentrations, zones of potential risk for methane explosion were identified in the goafs of this longwall and the tailgate. Additionally, a "what-if" scenario analysis was performed to determine the concentration of methane at the intersection of the longwall with the tailgate and to assess the risk of methane explosion in the goaf under emergency conditions. The scenario studied included a 15% increase in methane release compared to the planned scenario.

The results obtained offer significant potential for application in the diagnosis and prediction of methane hazard conditions in underground mining processes.

2. Materials and methods

The section presents the characteristics of the studied longwall and discusses the theoretical assumptions of the applied gas flow model, taking into account the flow through the porous medium. The developed structural model of the studied mining region is also presented.

2.1. Area of research

The longwall for which model tests were conducted using numerical fluid mechanics is located in the Upper Silesian Coal Basin. This longwall is ventilated by a Y system with air discharge along the goafs. Exploitation is carried out with a longwall system involving roof collapse in the direction from the boundaries of the mining field. The basic geometric parameters of the longwall are:

- longwall length: 250.0 m,
- total longwall enclosure: approximately 870 m,
- height: 2.0 m

Table 1 provides a summary of the physicochemical parameters of the rocks at the floor and roof of the mined seam. The susceptibility of these rocks to sparking, which can ignite methane both in the longwall and in the goafs due to significant variation in their quartz content, was determined to be high. Additionally, the initial temperature of the rocks, located at a depth of 780 meters, was 23 ºC.

Table 1. Physical and chemical parameters of rocks deposited at the floor and roof of the exploited seam

Type of rock	Zone	R_c, MPa	Density, g/cm^3
clay shale (siltstone)	mine roof	41.6	2.65
coal (non-marine seam)	mine roof	17.5	1.28
clay shale (siltstone)	mine roof	26.6	2.50
coal (seam 405/1)	seam	17.5	1.28
clay shale (siltstone)	mine floor	31.7	2.56

The seam in which the mining was carried out was classified as a category III methane hazard according to Polish regulations, indicating a high level of risk. The longwall was ventilated with air supplied at a rate of approximately 1,200 m³/min via a maingate. Additionally, air was supplied through the tailgate (in the area of the longwall air outlet) at a rate of about 450 m³/min. Methane discharge into the longwall averaged around 13 m³/min during the operational period.

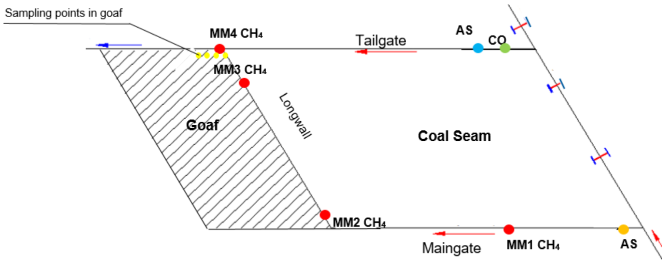


Fig. 1. Schematic of the longwall under test with marked airflow directions and sensor locations of the automatic gasometry system (own elaboration)

2.2. Numerical model

2.2.1. Mathematical model of gas flow through longwall

The mixture of gases (air and methane) flowing through the longwall region and adjacent goafs is governed by the fundamental equations of flow, namely the equations of mass conservation, momentum conservation, and chemical transport. Additionally, the flow is described by equations that account for turbulence. In this study, the standard k-epsilon (k-ε) turbulence model was selected. This model is commonly used in gas flow simulations due to its simplicity and reliability, particularly when modelling flows in free shear layers with minor pressure gradients (Brodny and Tutak, 2015; Qiao et al., 2022). The basic equations of the flow model adopted for the study take the following forms (Ansys, 2018):

1) Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{\boldsymbol{u}}) = S_m \tag{1}$$

where: ρ denotes the density of mixed air and gases (kg/m^3), t is time (s), S_m represents the mass added to the continuous phase from the dispersed second phase (kg/(m^2-s)) if the dispersed second phase is not present then S_m =0; $\vec{\boldsymbol{u}}$ is the component of velocity in three different directions (z, y, z) (m/s):

$$\vec{\boldsymbol{u}} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \tag{2}$$

2) Momentum conservation equation:

$$\rho\left(\frac{\partial \vec{\boldsymbol{u}}}{\partial t} + \vec{\boldsymbol{u}} \cdot \nabla \vec{\boldsymbol{u}}\right) = -\nabla p + \mu \nabla^2 \vec{\boldsymbol{u}} + F \tag{3}$$

where: ∇p is pressure gradient (Pa); μ is the coefficient of kinetic viscosity (Pa·s), F is volumetric force vector, $\rho\frac{\partial \vec{\boldsymbol{u}}}{\partial t}$ i $\rho\vec{\boldsymbol{u}} \cdot \nabla\vec{\boldsymbol{u}}$ is the component of the force due to the change in momentum and convective acceleration, $\mu\nabla^2\vec{\boldsymbol{u}}$ - is the viscosity component.

3) Species equation

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \cdot \vec{\boldsymbol{u}} \cdot Y_i) = -\nabla J_i + R_i + S_i \tag{4}$$

where: Y_i is local mass share of species i, J_i is species i diffusion flux, R_i is the net rate of production of species i by chemical reaction, S_i is rate of creation by addition from the distributed phase and any user-defined sources.

Equation (4) is solved for $n-1$ species, where n is the total number of chemical compounds in the liquid phase being modeled.

4) Turbulence model

The k-ε turbulence model of the standard variety is a two-variable model that includes two important parameters: turbulent kinetic energy (k) and turbulent dissipation rate (ε) (5 and 6):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - p\epsilon - Y_M + S_k \rho\epsilon - Y_M + S_k \tag{5}$$

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon\frac{\varepsilon}{k}}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon\rho\frac{\varepsilon^2}{k}} + S_{k\varepsilon} \tag{6}$$

where: G_k and G_b are turbulence kinetic energy generation due to gradients of mean velocity and buoyancy force, Y_M is the contribution of fluctuating dilation in elastic turbulence to the overall rate of dispersion, σ_k and σ_ε are the turbulent Prandtl numbers for k (with a value of 1.0) and ε (with a value of 1.3), S_k and S_ε - user-defined sources, $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are fixed values ($C_{1\varepsilon}$ =1.44, $C_{2\varepsilon}$ =1.92), μ_t is takes a constant value equal to 0.09.

2.2.2. Mathematical model of gas flow through the goaf

In Ansys Fluent, a porous medium (such as a goaf) is represented as a fluid characterized by two additional parameters: porosity and permeability coefficient. The inclusion of the porous medium in the study is accounted for by incorporating a source term S_i in the momentum conservation equation. This source term is represented by the general form of equation (7) (Chen et al., 2023):

$$S_{Di=-\left(\frac{\mu}{k}v_i + C_2\frac{1}{2}\rho|v|v_i\right)} \tag{7}$$

where: S_{Di} is the loss source term; k is the permeability of goaf; C_2 is the inertial resistance coefficient; v is the magnitude of the velocity.

The permeability of the goaf (k) was determined from equation (8):

$$k = \frac{\mu}{r_0 + ax^2} \tag{8}$$

where: r_0 and a are empirical coefficients depending on the mining and geological conditions of the collapse, which are determined from relations (9 and 10):

$$r_0 = \frac{\mu}{k_0} \tag{9}$$

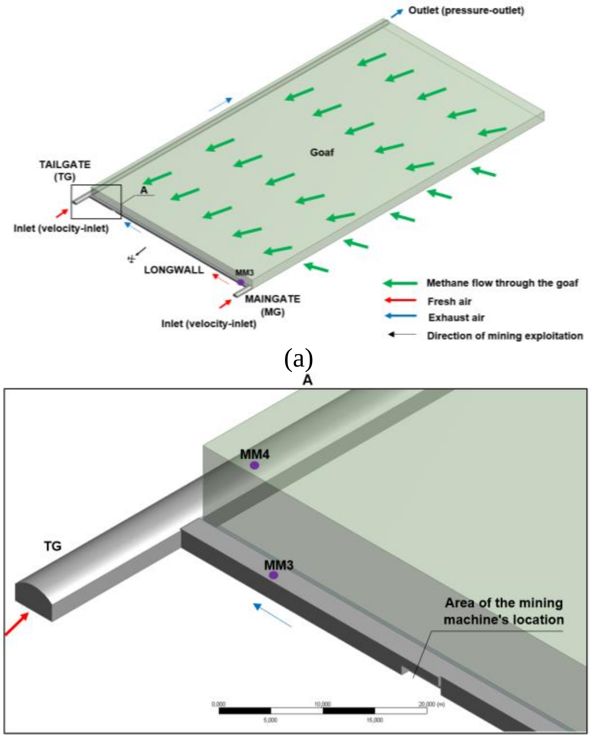
$$a = 6 \times 10^9 \times R_{rrs}{}^{-1.74} \tag{10}$$

where: R_{rrs} is the stratification resistance coefficient of the roof layers (dependent on the type of roof rock forming the collapse), MPa; k_0 is the value of the permeability coefficient of the goaf behind the working face:

$$k_0 = \frac{\mu}{6} \times 10^{-10} \times R_{rrs}{}^{1.44} \tag{11}$$

2.3. Problem statement and boundary conditions

In order to ensure the validity of the numerical analyses carried out, it is crucial to develop a structural model that represents the study area of the longwall along with its ventilation parameters. The geometric model took into account the longwall, the maingate, the tailgate and the goaf, and along with the conditions of unambiguity is shown in Figure 2. While the basic parameters of the computational model are given in Table 2.



(b)

Fig. 2. Geometric model of the tested longwall ventilated by the Y system with the adopted boundary conditions (a), including the tailgate (b) (own elaboration)

The inclusion of goaf and air flow through this area in the study necessitated determining the vertical extent of this flow. It is generally accepted that the zone of air flow through goaf extends from three to four times the thickness of the mined seam (layer). The height of this flow is determined by the extent of the so-called full collapse, which is equal to three times the thickness of the mined layer. Considering that air flow also occurs in the space of the selected longwall, a flow zone covering four times the seam thickness was established. However, taking into account the subsidence of the main roof by 0.5 to 0.6 times the seam thickness, it was assumed that the height of the air flow in the goaf is equal to 3.5 times the thickness of the exploited seam (layer) (Tutak and Brodny, 2019).

Table 2. Computational model geometry, basic setups for the numerical simulations and ventilation parameters of longwalls

Variable	Value/Detail
Airflow volumne rate - maingate, m /min^3	1200
Airflow volumne rate -tailgate, m /min^3	450
Methane emission rate from goaf, m /min^3	13
Working face - Geometric size x × y×z (m × m×m)	2.0×3×250
Maingate - Geometric size x × y×z (m × m×m)	3×5×20
Tailgate - Geometric size x × y×z (m × m×m)	3×5×410
Goaf - Geometric size x × y×z (m × m×m)	215×9×390
Temperature of fresh air, K	295,15
Temperature of wall, K	313,15
Oxygen concentration in inlet air flow (Maingate), %	21
Atmospheric pressure (MPa)	0.1
Air density (kg/m^3)	1.290
Methane density (kg/m^3)	0,657
Oxygen diffusion coefficient (m^2 /s)	1.78 × 10-5
Methane diffusion coefficient (m^2 /s)	1.00 × 10-5
Oxygen molar mass (kg/mol)	0.01599
Methane molar mass (kg/mol)	0.01604
Viscosity, Pa-s	$1.8 \cdot 10^{-5}$
Permeability of goaf (m2)	from 9.62×10^{-5} to 9.87×10^{-8}
Ventilation mode	"Y"-type
Solver type	Pressure-based
Time	Steady
Scheme	Coupled

Boundary conditions for "inlet" and "outlet" were defined in the longwall headings. An "inlet" type condition was set in two locations: maingate and tailgate, positioned 20 m from the longwall. This distance was assumed to be sufficient for the full development of the velocity profile of the air flow entering the longwall. The volumetric flow rate of the air supplied to the longwall was 1,200 m³/min, while the tailgate received 450 m³/min.

For the flow-longwall interactions, standard functions and zero flow velocity values were assumed for wall-type conditions (with walls treated as sidewalls). The surface roughness of these walls was set to 0.1 m, and their temperature, considered the temperature of the surrounding rock mass, was 23°C. The temperature of the air stream entering the workings was set at 22°C.

In the analyzed excavation systems, a methane flow rate of 13 m³/min was accounted for in the goaf. Methane sources in the goaf include gas expanded from adjacent coal seams and desorbed methane from coal residues.

The computational domain was divided into two parts: one representing the longwall and longwall excavations, and the other representing the goaf. In the goaf domain, the variation in porosity and permeability coefficient as a function of distance from the longwall front was defined using a created User Defined Function (UDF). The goaf was treated as a porous medium composed of collapsed roof rock blocks and remnants of unmined coal seams, with gaps (contacts between collapsed rock blocks) present. Gas migration and mass transfer within this medium depend on various factors. For this study, the goaf was modelled as an isotropic porous medium. The physical properties and chemical reactions of the gas were considered at a steady state, ignoring the influence of water on these phenomena. The physical properties of the coal and rock in the goaf were assumed to be constant over time, and methane evolution from the goaf was considered a continuous and stable process.

In the geometric model developed, machinery and equipment within the longwall and longwall excavations were skipped because their influence on the results of the methane hazard zone determination and concentration analysis in the intersection area of the longwall and tailgate was negligible.

In the next stage, the geometric model was discretized to divide the computational domain into finite volumes. The computational domain for the goaf was represented by a structured hexahedral mesh, while an unstructured three-dimensional tetrahedral mesh was used for the longwall and longwall excavations. The longwall layer was also incorporated into the model, including the sidewalls, floor, and roof of the workings, to more accurately represent the flow in these areas. Numerical simulations were conducted on a model consisting of 12,684,096 finite volumes (Figure 3). The minimum element quality value was 0.204 for 89 elements, and the maximum value was 0.958 for 4,440,000 elements.

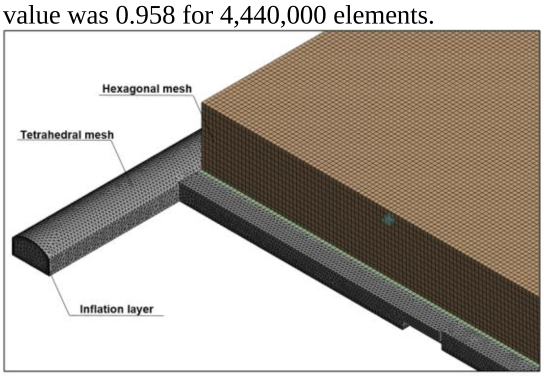


Fig. 3. The mesh of the goaf and the working face and tailgate zones (own elaboration)

All the simplifications adopted in the developed models in relation to real objects are due to their size and represent some compromise between the accuracy of the calculations and the time to obtain a solution.

The model thus developed, along with the assumed conditions of unambiguity, was subjected to numerical analysis.

3. Results and discussion

The section presents the results of the conducted research, including the case of increasing methane emissions from the longwall by 15%. After each stage of the research, a brief discussion was also conducted regarding the results obtained.

3.1. Characteristics of airflow through the region of the longwall ventilated by the system on Y

In the initial stage of the modeling study, flow trajectories were determined to illustrate the general nature of airflow through the longwall ventilated by the Y system and its goafs (Figure 4). Additionally, the distributions of air velocity (Figure 5) and turbulence kinetic energy (Figure 6) in the analyzed region were evaluated.

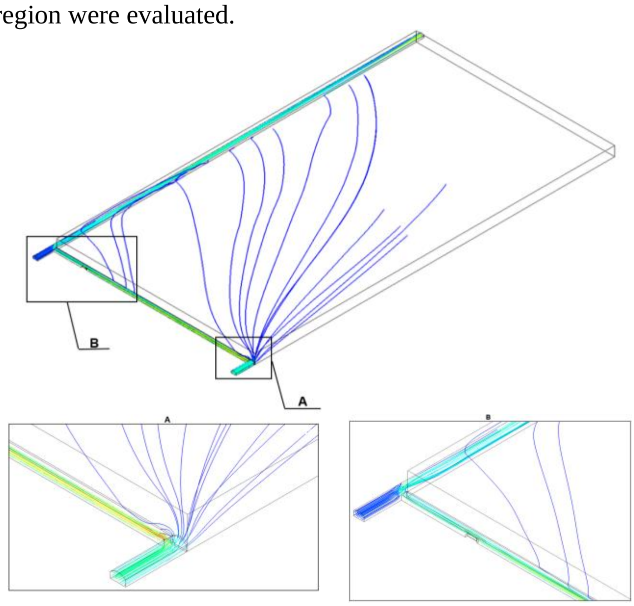
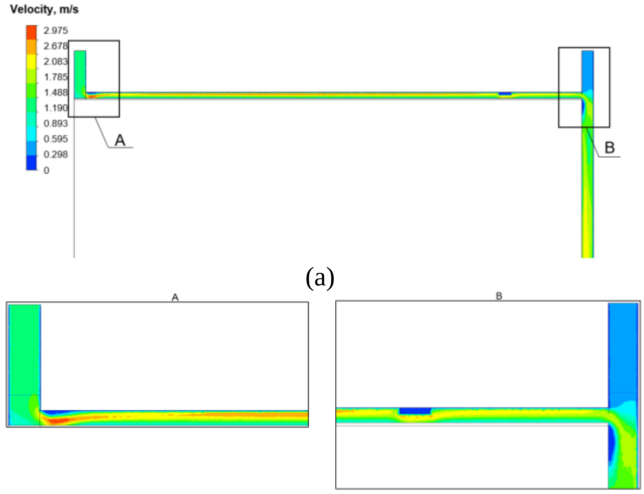


Fig. 4. Trajectories of air flow through the longwall, excavations, goafs
(own elaboration)

The flow trajectories reveal the direction of fresh air entering the mining region and its subsequent dispersion. As air enters the longwall, it changes direction by 90°, moving from the large cross-sectional area of the dog heading (13.5 m²) to the longwall excavation with a cross-sectional area of 9 m². A small portion of the air is directed towards the goaf, entering through leaks between the maingate and the goaf zone (Figure 4 - detail A). The main airflow proceeds through the longwall and, upon exiting, changes direction by another 90° to merge with the air supplied by the tailgate (Figure 4 - detail B).

The air stream exiting the longwall enters a larger cross-sectional area, and it has a higher velocity (Figure 5) and, consequently, greater kinetic energy (Figure 6) compared to the lower-velocity stream supplied by the tailgate (Figure 5). When these two streams meet, the higher-velocity stream increases the velocity of the slower stream. After approximately 8 meters of the dog heading, the air velocities in both streams begin to stabilize.

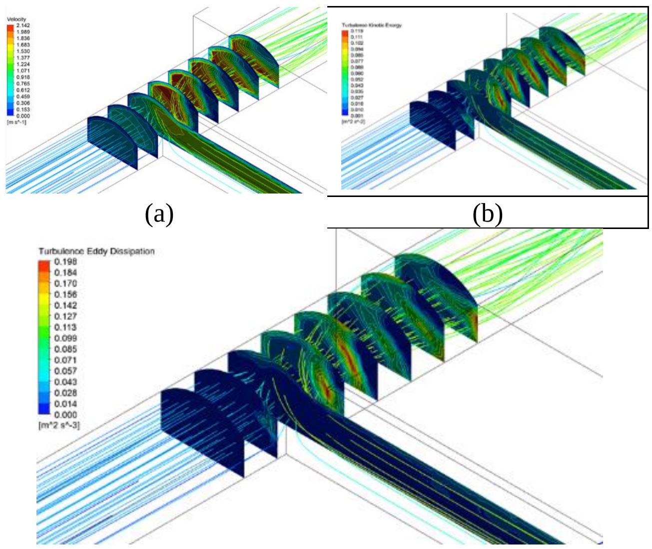
It can be observed that the air exiting the longwall and merging with the airflow from the tailgate (Figure 4, detail B; Figure 5) does not evenly fill the entire cross-section of the longwall workings. The combined air streams of different velocities in the section of the tailgate, located just behind the intersection, tend to align with the sidewall that does not border the goaf. This phenomenon is related to the Coanda effect (Hu et al., 2020; Wang et al., 2018). As the airflow moves away from the intersection of the longwall and the tailgate, it gradually fills the entire cross-section of the workings.



(a)

(b) (c)

Fig. 5. Distribution of air velocity in the longwall workings (a) and face workings (b and c) in a plane located at a height of 1.1 m from the mine floor (own elaboration)



(a) (b)

(c)

Fig. 6. Air velocity distributions (a), turbulent kinetic energy (b) and turbulence eddy dissipation (c) in the tailgate (longwall air outlet) (own elaboration)

The nature of the airflow through the excavation system under study influences the pressure distribution in the goaf, particularly in regions adjacent to the maingate and tailgate. These pressure variations affect the velocity of airflow through the goaf (filtration phenomena), which directly impacts both the methane hazard and the risk of spontaneous combustion of coal in the goaf (Liang et al., 2023). Static pressure distributions for the studied longwall region are illustrated in Figure 7.

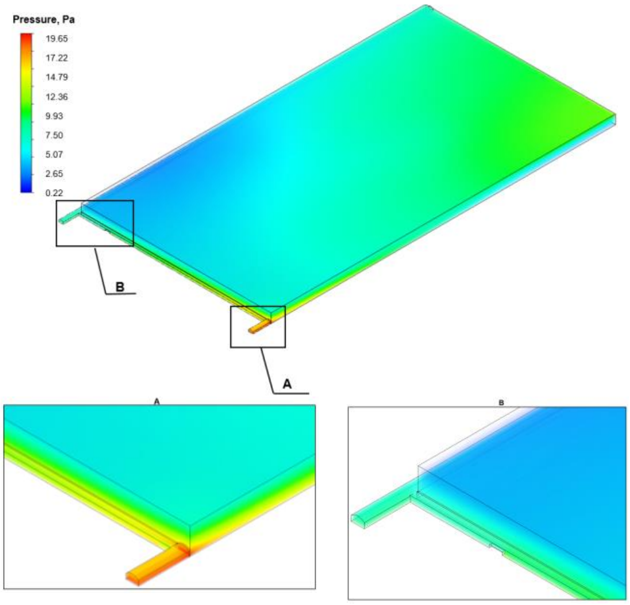


Fig. 7. Distribution of static pressure in the longwall region (own elaboration)

Based on the determined distributions of static pressure values, it can be concluded that, excluding the areas around the wall inlet and outlet (the lower and upper corners of the longwall), the pressure drop exhibits a linear nature. The significant, non-linear decreases in static pressure observed near the wall inlet and outlet are attributed to the aforementioned changes in the cross-sectional area of the workings. In contrast, the static pressure in the longwall workings demonstrates a linear drop along its entire length

3.2. Distribution of methane in the tailgate (longwall air outlet region)

The calculations determined the distributions of methane concentrations in the tailgate, at the outlet of the longwall ventilated by the Y system. As previously mentioned, the merging of two air streams with different velocities occurs in this area. This phenomenon, combined with the Coanda effect, directly impacts the methane concentration distribution in the tailgate, where methane also migrates from the goaf collapse region. Methane, being lighter than air, tends to accumulate in the upper parts of the workings. However, this occurs only when the air stream uniformly fills the entire cross-section of the workings, which is not the case in the analyzed region.

The highest methane concentrations are observed up to 8 meters from the air outlet of the longwall, especially at the sidewall to the goaf (Figure 8). In this area, a poorly ventilated zone promotes local methane accumulation. After approximately 8 meters into the heading, the combined air streams begin to fill the entire space more evenly. At this point, methane accumulation shifts to the upper part of the heading, rather than at the side as seen directly behind the longwall air outlet. This change in methane distribution is due to improved airflow in the workings, enhancing ventilation and reducing local gas accumulations.

The highest methane concentration was recorded on planes perpendicular to the excavation axis, located 2 and 3 meters from the longwall air outlet. This concentration exceeded 1.4% CH_4, with a methane outflow rate from the goaf of 13 m^3/min (Figure 8).

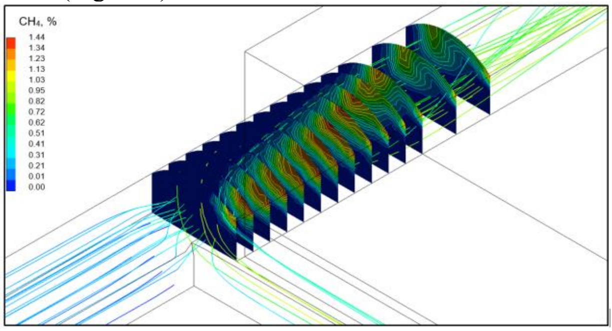


Fig. 8. Distribution of methane concentration in the tailgate at the outlet of the longwall ventilated by the Y system, shown on vertical planes located at 1.0 m intervals (with methane outflow from the goaf at 13 m^3/min) (own elaboration)

To assess the impact of increased methane outflow from the goaf at the intersection of the longwall and the tailgate, an additional "what-if" scenario analysis was conducted. In this scenario, it was assumed that methane outflow increased by 15% compared to the actual value, resulting in a methane outflow rate of 14.95 m^3 per minute into the workings from the goaf. This analysis allows for the evaluation of the effects of increased methane outflow in the study area. The results of this analysis are illustrated in Figure 9.

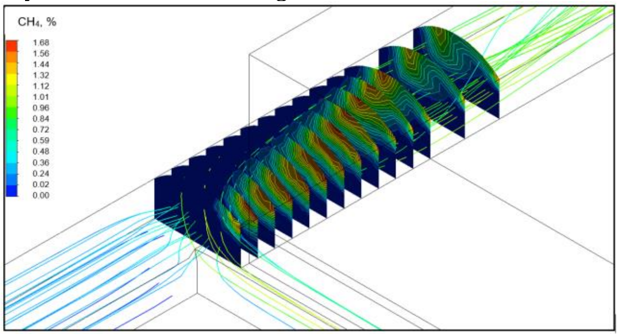


Fig. 9. Distribution of methane concentration in the tailgate at the outlet of the longwall ventilated by the Y system, shown on vertical planes located at 1.0 m intervals (with methane outflow from the goaf at 14.95 m^3/min) (own elaboration)

Analysis of this potential condition indicates that, even with a 15% increase in methane outflow into the workings space, the permissible values set by mining regulations (Regulation of the Minister of Energy, 2016) will not be exceeded. In this scenario, the highest methane concentrations will be approximately 1.7%, assuming that the air supply remains unchanged.

To evaluate the effectiveness of the model tests, a validation process was conducted by comparing methane concentrations recorded by sensors at measurement points with those determined from the model tests. The results of this comparison, including the associated errors, are summarized in Table 3.

The relative error between the methane concentrations recorded by the automatic manometry sensors and those obtained through numerical calculations ranged from 5% to 11%. The greatest discrepancy was observed at point MM3, situated 10 meters from the longwall outlet. These discrepancies could be attributed to the model's simplifications and the measurement uncertainty of the methanometry system. However, the recorded differences, which are less than 12%, fall within an acceptable range. Thus, it can be concluded that the developed model accurately represents the studied phenomenon

Table 3. Comparison of methane concentration values obtained from model tests and recorded by automatic methanometry sensors

Measurement points	Methane concentration, % Field Investigations	Numerical model	Error, %
Point MM-2	0.2	0.19	5%
Point MM-3	0.7	0.63	11%
Point MM-4	1.4	1.48	6%

3.3. The distribution of oxygen and methane concentration in the longwall goaf

The study also assessed the distribution of oxygen and methane concentrations in the goafs of the longwall under investigation.

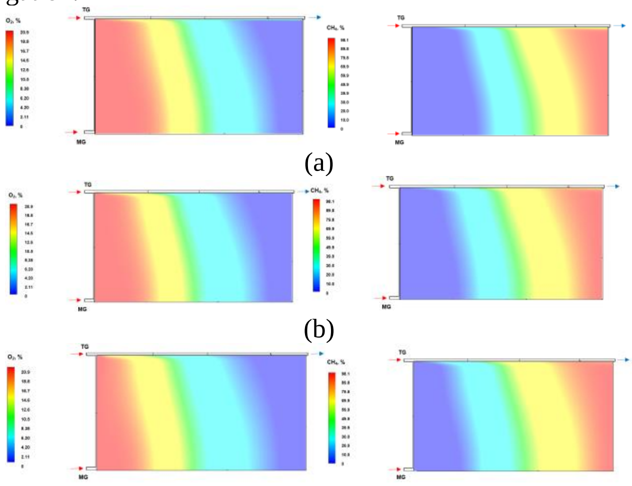
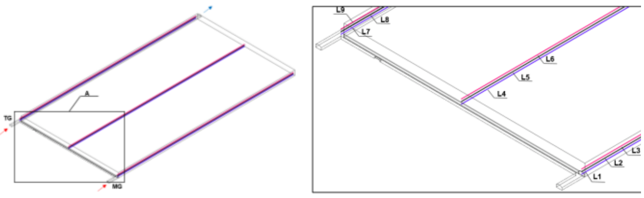


Fig. 10. Oxygen and methane concentration distributions in goafs on planes located at 1m (a), 3m (b) and 5m (c) from the mine floor (own elaboration)

The results reveal that high oxygen concentrations are present along the entire length of the longwall, both on the inlet and outlet sides (Figure 10). This can be attributed to the migration of oxygen-rich air deep into the goaf due to leaks at the interface between the longwall space and the goaf. These leaks facilitate the free flow of air between the two areas, leading to elevated oxygen levels in the goaf.

As one moves further from the longwall face, oxygen concentrations in the goaf decrease (Figure 10). This decrease is due to the reduced permeability of the goaf and the rising methane concentration. These factors hinder the migration of air into the goafs, resulting in higher methane levels. Additionally, the increase in methane concentration further into the goafs is driven by methane release from residual coal and migration from adjacent seams.

In order to identify the zone of potential danger of explosive methane concentration in the goaf (with a minimum oxygen concentration of 12%), the model adopted three measurement lines located at distances of 1, 3, and 5 meters from the bottom of the seam. Measurement lines 4-6 were positioned exactly in the middle of the longwall length (225 meters), while measurement lines 1-3 and 7-9 were situated at a distance of 2.5 meters from the boundaries of the goaf area. The layout of these measurement lines is shown in Figure 11.



(a) (b)

Fig. 11. Distribution of measurement lines in the model (own elaboration)

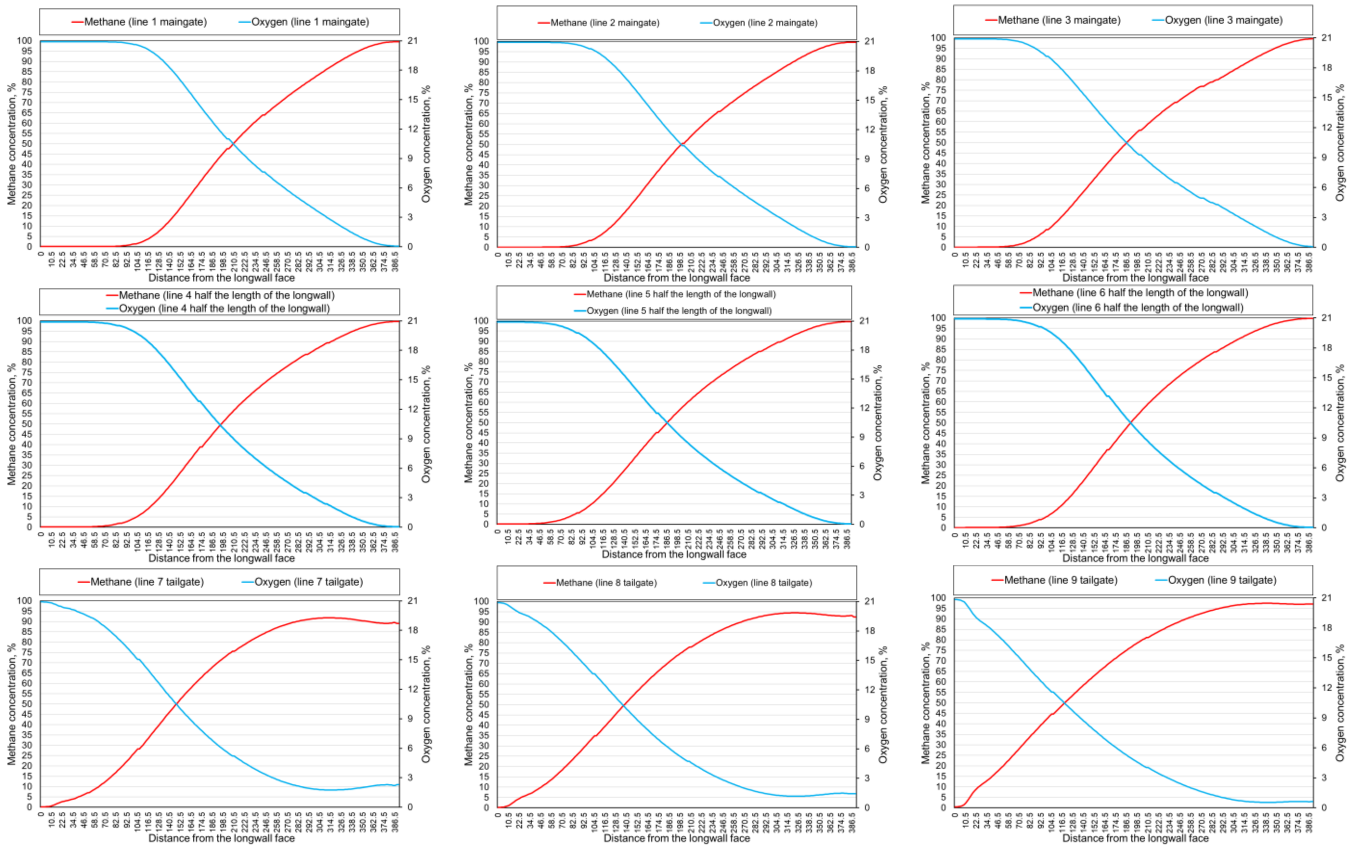
Figure 12 shows the changes in methane and oxygen concentrations in the levees at 1.0 m, 3 m and 5 m along the measurement lines shown in Figure 11.

The determined distributions provide an opportunity to assess whether the conditions necessary for the occurrence of a fire and/or methane explosion are met. In this case, it should also be remembered that an initiating impulse is necessary for such an event to occur.

The obtained calculation results were compared with the results of the composition of air samples taken from the goaf (Table 4). The data presented and the results of relative error calculations, for calculations and actual measurements show the same trends—the farther away from the face of the longwall, the more the oxygen concentration decreases. The error value does not exceed 2% in this case. For methane, the recorded differences are slightly larger, but the relative error does not exceed 10%.

Table 4. Comparison of the results of calculations with the results of the composition of air samples taken from the goaf

Distance of measuring point in the goaf from the front of the longwall, m	Oxygen, % Measurement	Oxygen, % Result of calculation	Oxygen, % Error, %	Methane, % Measurement	Methane, % The result of calculation	Methane, % Error, %
0	20.74	20.9	1%	0.11	0.10	10%
1	20.72	20.9	1%	0.09	0.10	10%
3	20.71	20.9	1%	0.11	0.10	10%
5	20.7	20.8999	1%	0.11	0.10	10%
7	20.66	20.8997	1%	0.11	0.10	9%
9	20.66	20.8995	1%	0.1	0.10	2%
11	20.56	20.8993	2%	0.11	0.10	6%
13	20.49	20.8991	2%	0.11	0.10	6%



(a) (b) (c)

Fig. 11. Changes in the methane and oxygen concentrations in goaf under a gas emission of 13m^3/min (own elaboration)

Therefore, it can be concluded that the developed model and the obtained results have acceptable accuracy and can be used in practice to identify the methane hazard. The goaf area that simultaneously has a minimum of 12% oxygen concentration and 5% to 15% methane concentration is an area with a potential risk of explosion of this gas, in the event of an ignition-initiating source (such as a spark coming from collapsed blocks of roof rock containing significant amounts of quartz). In three-dimensional space, these conditions can be written as follows:

$$\text{Risk of methane explosion in goaf} = \left\{ \begin{matrix} (x,y,z) \in \mathbb{R}^3: \\ O_2(x,y,z) \geq 12\% \wedge 5\% \leq CH_4(x,y,z) \leq 15\% \end{matrix} \right\} \quad (12)$$

This area on each plane in turn is defined by the following condition (13):

$$\text{Risk of methane explosion in goaf} = \left\{ \begin{matrix} (x,y) \in \mathbb{R}^2: \\ O_2(x,y) \geq 12\% \wedge 5\% \leq CH_4(x,y) \leq 15\% \end{matrix} \right\} \quad (13)$$

Table 4 shows the area of the formation of this zone in planes located in the goaf at heights of 1m, 3m and 5m from the bottom of the deck along the designated measurement lines.

Table 5. Methane explosion hazard zone in goaf

Measurement location	Height of the measurement plane from the floor of the excavation, m		
	1.0	3.0	5.0
Along the line located on the maingate side	121.0-145.0	108-134	87-116.5
Along a line located halfway down the longwall	103.5-130.5	86.0-116	97.5-125
Along the line located on the tailgate side	40-78.0	24-61	15-40

The analysis shows that the extent of the methane explosion risk zone varies depending on the height in the goaf and the area of the goaf. Along the line located on the maingate side, the methane explosion risk zone is furthest from the longwall workings at each of the analyzed heights. In contrast, along the line located on the tailgate side, the explosion risk zone is located, in turn, closest to the longwall face. This is due to the aforementioned nature of air migration into the goaf, which is most intense from the maingate side. As a result, the distribution of oxygen concentrations is somewhat more extensive in this zone than on the tailgate side, and the concentration of methane with explosive levels is farther away from the front of the longwall. On the other hand, on the tailgate side, the zone at risk of methane explosion is located closest to the front of the longwall. At a height of 3.0 meters, it is located only 24 meters from the front of the longwall. The results also show that, in general, the zone is formed over a very long length (about 30 meters) on each analyzed plane.

In order to assess the impact of increased methane emissions on the state of methane risk in goaf, a "what-if" scenario analysis was conducted. Its purpose was to determine how the methane explosion risk zone in the goaf would change if methane emissions increased. As part of the analysis, similar to the study of the distribution of methane concentration in the longwall workings, the volume of methane release from the goaf was increased by 15%, resulting in 14.95 m³/min of methane.

Such an analysis is crucial because an increase in methane concentration in goafs (e.g., due to increased stress in the rock mass) can lead to dangerous levels. Figure 13 illustrates the distributions of oxygen and methane concentrations in goafs under this increased emission scenario. Meanwhile, Figure 14 depicts the changes in methane and oxygen concentrations in the goafs at heights of 1.0 m, 3 m, and 5 m along lines passing through the centre of the lonwall (lines 4, 5, and 6 as shown in Figure 11).

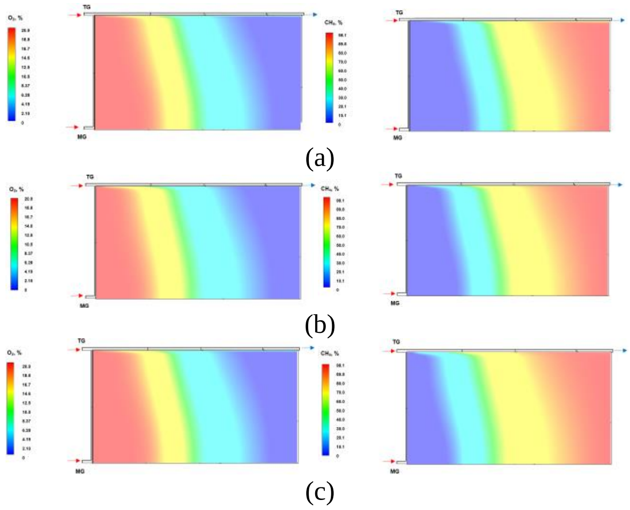


Fig. 13. Oxygen and methane concentration distributions in goafs on planes located at 1m (a), 3m (b) and 5m (c) from the mine floor (own elaboration)

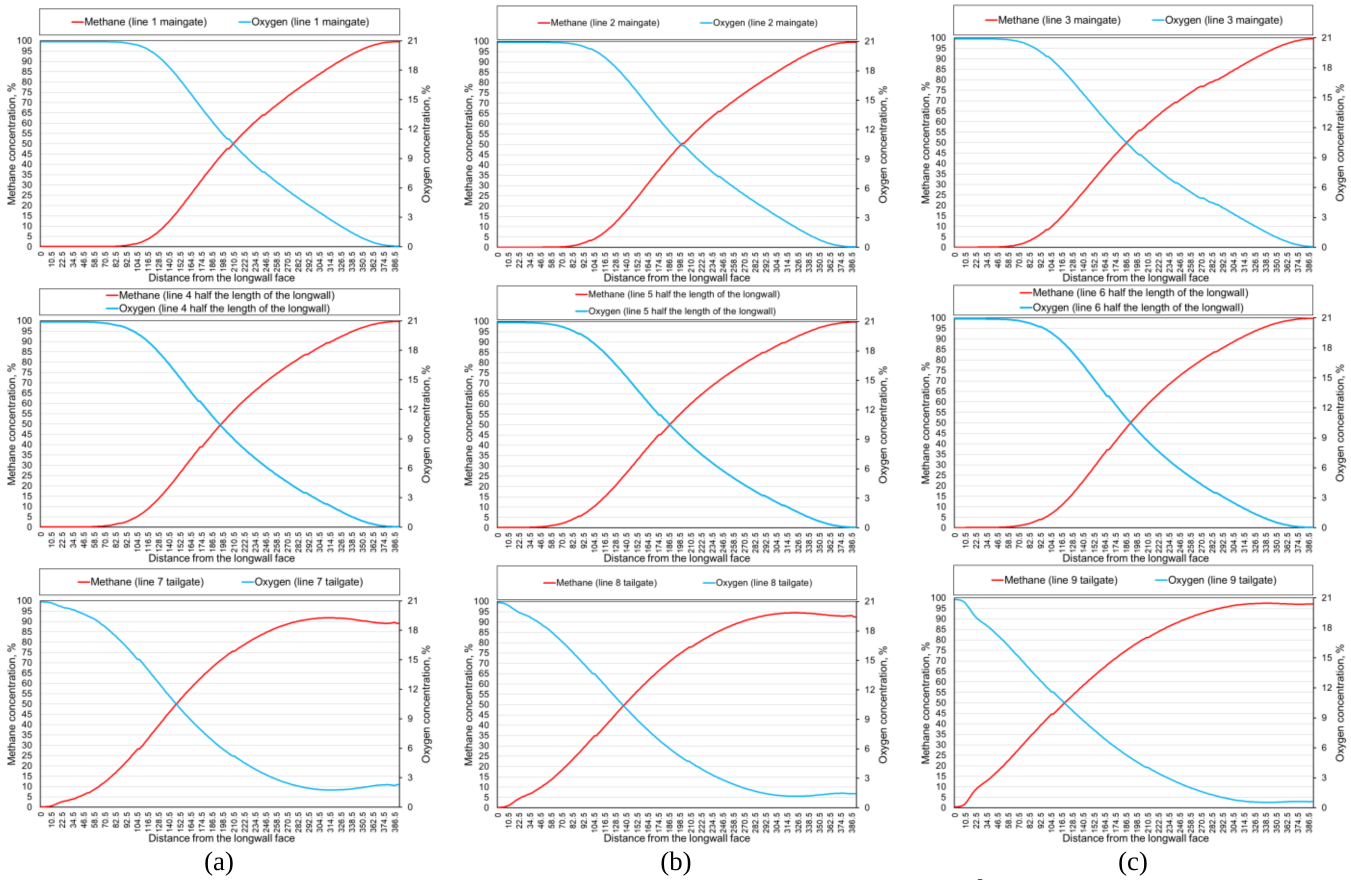


Fig. 14. Changes in the methane and oxygen concentrations in goaf under a gas emission of 14.95 m^3/min at heights of 1m (a), 3m (b) and 5m (c) from the mine floor (own elaboration)

Table 6 shows the areas of formation of the methane danger zone at heights of 1m, 3m and 5m from the floor of the seam along the designated measurement lines (Figure 11) for an example of increased methane emissions.

Table 6. Methane explosion hazard zone in goaf for alternative calculation option

Measurement location	Height of the measurement plane from the floor of the excavation, m		
	1.0	3.0	5.0
Along the line located on the maingate side	116-139	106-130	85-113
Along a line located halfway down the longwall	99-124	82-109	86.5-113
Along the line located on the tailgate side	36-72	21.5-56	14-35

For the alternative calculation variant with increased methane emissions, the zones at risk of methane explosion in goafs are located closer to the longwall. This shift occurs because higher methane concentrations in the goaf lead to an increased risk zone proximity to the longwall face. Despite this shift, the zone remains closer to the front of the longwall in the goaf section adjacent to the tailgate. This pattern reflects the inherent nature of air migration and methane distribution dynamics in the goaf, where increased methane concentration exacerbates the risk of explosive conditions, particularly nearer to the tailgate.

4. Conclusions

Methane hazard is one of the most dangerous hazards that occur during underground coal production. Methane, as a highly flammable and explosive gas, poses a major threat to the effective implementation of the mining production process and to the crew. Therefore, any work that provides an opportunity to improve the state of methane safety is of great and positive importance. Currently, to identify zones at risk of fire and/or explosion of methane, in addition to traditional measurement methods, model tests based on numerical simulations are used, which allow precise determination of concentration distributions of this gas in mining regions. The prerequisite for obtaining acceptable results is the correct representation of the geometry and physical and chemical conditions of the studied region and the phenomena occurring in it. Meeting these requirements provides opportunities to obtain results that can support the process of risk management and the entire operation process.

Of key importance in this process is the identification of zones of potential fire and/or explosion hazard, especially in areas where direct measurements cannot be taken, i.e. in goafs. This is important because the accumulation of methane in goafs and its migration into the workspace can cause very dangerous states of emergency.

Referring to this extremely important and topical subject, the paper presents the developed methodology for determining the zones of potential explosion and methane fire hazard, as well as the results of studies of a specific mining region. The research was carried out based on the structural model of this region using the finite volume method. The study was carried out for a longwall ventilated with the Y system, for actual ventilation parameters and for a variant involving increased methane emissions.

The result of this work was the distributions of methane and oxygen concentrations in the studied workings and goafs, treated as a porous and permeable medium. These distributions also made it possible to determine the extent of the danger zone of a potential methane explosion in these goafs.

Based on the methodology developed, the research conducted, and the results obtained, the following main conclusions were made:

– The highest concentration of methane is found in the tailgate, up to 8 meters behind the longwall air outlet. Methane accumulates at the sidewall of this excavation adjacent to the goaf. This is due to the fact that this is a zone very poorly ventilated by the air flow. Such a phenomenon occurs despite the tailgate's supply of an additional air stream to the outflow region, which combines with the stream flowing out of the longwall. However, this phenomenon contributes to some local disturbances and the Coanda effect, which causes the combined airstreams to adhere to the opposite sidewall, i.e., the side not bordering the goaf. It is only when moving away from the area of the intersection of the longwall and the tailgate that the air stream fills the entire cross-section of the workings, causing more effective ventilation.
– The location of the zone associated with the risk of methane explosion in goafs is not the same throughout their area. This zone is closest to the working space of the longwall in the vicinity of the tailgate and is furthest from the front of the longwall behind the maingate. At higher altitudes, the extent of the methane explosion hazard zone approaches the front of the longwall. This is related to the occurrence of higher concentrations of methane and, at the same time, weaker air filtration phenomena in goafs. The location of this zone in the goaf also depends on the amount of methane emitted from the goaf. In the case of a higher amount of this gas, the danger zone is located closer to the front of the longwall.

In summary, it can be said that the use of structural model studies provides great opportunities for diagnosing and forecasting methane hazard conditions. The results obtained indicate that such activities should significantly support the operation of methane services in mines, influencing the improvement of work safety and the efficiency of the implementation of mining processes.

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