Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

Applying CFD Model Studies to Determine Zones at Risk of Methane Explosion and Spontaneous Combustion of Coal in Goaves

Magdalena TUTAK[1]*, *Jarosław BRODNY*[2] and *Greg GALECKI*[3]

Authors' affiliations and addresses:
[1] Silesian University of Technology, Akademicka 2A, 44-100 Gliwice, Poland
e-mail: magdalena.tutak@polsl.pl

[2] Silesian University of Technology, Akademicka 2A, 44-100 Gliwice, Poland
e-mail: jaroslaw.brodny@polsl.pl

[3] Missouri University of Science and Technology, 1006 Kingshiqhway, Rolla, MO 65409, United States
e-mail: ggalecki@mst.edu

***Correspondence:**
Magdalena Tutak, Silesian University of Technology, Akademicka 2A, 44-100 Gliwice, Poland
e-mail: magdalena.tutak@polsl.pl

How to cite this article:
Tutak, M., Brodny, J. and Galecki, G. (2022) Applying CFD Model Studies to Determine Zones at Risk of Methane Explosion and Spontaneous Combustion of Coal in Goaves. *Acta Montanistica Slovaca,* Volume 27 (3), 651-666.

DOI:
https://doi.org/10.46544/AMS.v27i3.07

Abstract

Underground mining operations are subject to a number of natural hazards. Events resulting from these hazards are difficult to predict, and if they occur, they disrupt the entire mining process and pose a great danger to the crew. Some of the most dangerous include ventilation hazards involving methane explosions and fires caused by the spontaneous combustion of coal. The complex state of the underground environment means that these hazards oftentimes occur simultaneously, making mining conditions even worse. The following paper addresses this issue by developing the methodology for determining areas endangered by methane explosions and spontaneous coal combustion in goaves. The reference to goaves results from the fact that this particular area is most frequently affected by spontaneous coal combustion and the accumulation of dangerous amounts of methane. The developed methodology was based on model tests with the use of the CFD method and data necessary to develop a numerical model. The research encompassed a real longwall in one of the hard coal mines, ventilated with the Y system during its exploitation, which is beneficial in the case of the methane hazard but worsens the safety in terms of the self-ignition of coal. As a result of the conducted research, for the exploitation conditions, dangerous zones were specified due to the potential possibility of methane explosion and self-heating of coal. The basis for determining dangerous zones was the criteria of occurrence of the examined phenomena. In this study, the zones were identified for each of the investigated hazards separately and for their simultaneous occurrence. Thus, the aim of the study, which involved the determination of potentially hazardous zones by applying modern methods of modelling in the mining area, was achieved. The results are an immensely important source of information for activities aimed at improving safety in the studied area in relation to the studied threats.

Keywords

methane hazard, spontaneous combustion of coal, CFD, prognosis, goaves.

Introduction

The process of underground mining disturbing the balance in the primary rock mass generates many natural hazards (Agboola et al., 2020; Li et al., 2021, Abramov et al., 2015; Kovanič et al., 2013; Urban et al., 2019; Kovanič et al., 2021). These hazards, combined with technical hazards resulting from applied mining technologies and technical equipment, cause many dangerous events to occur during the process in question (Kopas, Blatnicky et al., 2017). From the point of view of consequences, events resulting from natural hazards are particularly dangerous, as they have an immensely negative impact on both the safety and efficiency of the mining process (An et al., 2021; Brodny and Tutak, 2022; Cheng et al., 2021; Kwilinski and Kuzior, 2020). Therefore, in underground hard coal mines, as in other mines, preventive measures aimed at limiting the effects of occurring hazards are of great importance.

In the case of natural hazards, the very dangerous ones are ventilation hazards which include methane, climatic and fire hazards (Zhang et al., 2021, Cernecky et al., 2015). In this group, methane and the spontaneous combustion of coal, which oftentimes occur simultaneously during mining exploitation, are particularly hazardous (Saga, Blatnicka et al., 2020). The co-occurrence of natural hazards is a very common phenomenon reported during coal mining, significantly worsening the safety of its exploitation (Brodny and Tutak, 2016; Lu et al., 2022). The simultaneous occurrence of methane hazards and coal spontaneous combustion (endogenous fire) is exceptionally dangerous, as prevention processes for these hazards in many areas are mutually exclusive (Tutak et al., 2020; Qiao et al., 2022). As a result (Abd Ali et al., 2021), activities connected with methane hazard reduction may worsen safety conditions in terms of the coal spontaneous combustion hazard and vice versa (Yang et al., 2018; Zawadzki et al., 2013). Unfortunately, the complexity of the environment in which mining exploitation is carried out causes such situations to occur quite frequently (Saga, Blatnicky et al., 2020). This makes it necessary to apply very well thought-out, monitored and continuously supervised preventive measures. It is particularly important due to the possibility of methane ignition and/or explosion – dynamic phenomena, the consequences of which may be very tragic (Saga, Jakubovicova, 2014).

The simultaneous occurrence of the methane hazard and spontaneous coal combustion is particularly dangerous in the goaf areas (Gao et al., 2021; Li et al., 2018). The spontaneous combustion of coal is caused by its self-heating (leading to an increase in temperature). This process is facilitated by the coal's ability to absorb oxygen and release heat at the same time (Kopas, Saga et al., 2017). If the heat of the oxidation reaction is not dissipated fairly quickly, the temperature of the coal will continue to rise, leading to ignition. This phenomenon is most dangerous in goaves (Sapietova et al., 2011), which are poorly monitored due to limited access. The process of coal self-heating is a process of oxidation, which can also occur at low temperatures. Coal spontaneous combustion (endogenous fire formation) is thus a process of an uncontrolled increase in its temperature due to oxidation (Lu et al., 2022; Onifade and Genc, 2020). As a result, a product of incomplete coal combustion is released into the mine atmosphere in the form of poisonous gas – carbon monoxide. This gas can create an extremely dangerous atmosphere which is unfit for breathing (Handrik et al., 2017). The spontaneous combustion of coal can also be a very dangerous consequence of this process and can initiate the ignition and/or explosion of methane gas present in the area in question (Saga, Vasko, 2009). When a mixture of air and methane within its explosive limits (5%~15% CH_4) forms and persists near the coal self-heating area, the explosion of this gas can be initiated by energy generated by the coal self-heating and self-igniting (Gao et al., 2021; Zhu et al., 2022). And this, in turn, can bring disastrous consequences to the mine crew and equipment, significantly disrupting the whole mining process (Kundu et al., 2016). The history of mining knows many such events, which have been widely presented in the literature (Zhang et al., 2016). At this point, however, it is worth mentioning the last such event in Poland, which took place in the Pniówek coal mine, where on April 20, 2022, multiple methane explosions caused huge material losses and the death of 9 miners (as of April 29, 2022) as well as injuries to over a dozen others . (Wiecek, Burduk et al., 2019). Another 7 people were declared missing, leaving them behind a dam isolating the blast zone from the rest of the active mine mine (Saga, Vasko et al., 2014). The lack of an official report on the exact causes of this event makes a deeper analysis impossible, but it does indicate the catastrophic nature of this type of event resulting from the occurrence of combined hazards.

For this reason, activities and work of all types, including particular scientific work, aimed at developing methods to diagnose and forecast the risk status in the process of mining exploitation are of particular importance (Burduk, Wiecek et al., 2021). The result of applying such methods is the improvement of safety, among other things, through actions taken by appropriate dedicated services to prevent dangerous events.

In the case of the risk of spontaneous coal combustion, preventive measures are most frequently taken during mining operations, mainly by injecting inert gases and/or ash/foam into goaves. It is aimed at inhibiting or possibly limiting the process of spontaneous combustion of coal by triggering a cooling reaction and decreasing the contact between oxygen and coal (Deng et al., 2018; Zhou et al., 2013; Zhu et al., 2011) and at the same time neutralizing the atmosphere in the goaf. However, for these actions to be fully effective, they should be taken before the coal self-heating process is initiated and not during it. Therefore, in order to meet this condition, it is necessary to undertake prognostic actions, the aim of which should be to determine, already at the stage of designing exploitation, zones (areas) potentially endangered both by the accumulation of explosive concentrations of methane in goaves and by the self-ignition of coal.

It is important to note that at the design stage, as well as during the operation process, the determination of such zones based on tests and measurements in real conditions is very difficult and, in many cases, practically impossible (Segota et al., 2020). Therefore, it becomes necessary to use other alternative research methods which will make it possible, for example, model tests based on structural models and numerical simulations. Simulations are widely used research tools, which are more and more commonly being utilized in many areas of both research and practice. To a larger and larger extent, they are also being used for variant analyses of processes connected with the prognosis of various hazards in hard coal mining and for the analysis of emergency conditions, such as the occurrence of zones in the underground environment that are endangered by the spontaneous combustion of coal and methane explosion in goaves.

From the point of view of methane and endogenic fires threat, goaves are of key importance. The analysis of incidents so far has shown that the most dangerous incidents connected with these hazards are reported in these areas. Therefore, goaves, as a highly porous and permeable medium – and at the same time very difficult to monitor – are of key significance for developing coal spontaneous combustion and methane explosions. The system of ventilating a longwall, which determines the way of marking dangerous zones, is also significant, especially in the case of the simultaneous occurrence of these threats.

So far, in the literature, much attention has been paid to the issue of coal spontaneous combustion hazard and somewhat less to the methane hazard in goaves, using model tests. These publications are mainly focused on determining the distribution of physical and chemical parameters of air flowing through goaves, which results from the fact that these parameters are the basis for assessing the threat of coal spontaneous combustion and methane explosions.

The literature so far has provided a lot of scientific information on air flow through goaves and its distribution of gas concentration for longwalls ventilated from the boundaries, mainly with the U system and very rarely with the Y system. Liu et al. (2013) carried out numerical studies for longwalls ventilated with U and Y systems in order to characterize the airflow through goaves. Tutak and Brodny (2019) investigated the influence of roof rock type on the distribution of oxygen concentration and velocity of air flowing through goaves for longwalls ventilated with the Y and U systems. Li et al. (2020) conducted research in order to determine the volume flow rate of air migrating to goaves of a longwall ventilated with the Y system. On the other hand, Zhou et al. (2020) numerically investigated the oxygen distribution in the goaf area for a longwall ventilated with the U system and proposed the use of integrated fire prevention measures, including nitrogen and inhibitor injection and plugging of air migration sites into goaves. On the other hand, Zhang et al. (2020) conducted a study on the U-ventilated longwall to improve the knowledge of oxygen and temperature distribution in the goaf area of this longwall.

The presented selected works confirm that the issue of determining the distribution of physical and chemical parameters of air flowing through goaves is extremely important in terms of assessing the threat of spontaneous combustion of coal in the area of the conducted exploitation. However, the literature so far has not provided sufficient knowledge of the development of the methane fire hazard in the goaf areas, also in the case of simultaneous occurrence of coal spontaneous combustion hazard. There is also a lack of studies on forecasting the existence of potential zones with a risk of coal spontaneous combustion and methane explosions in the case of using the Y ventilation system in a longwall. Longwalls ventilated with this system are more and more commonly being exploited due to the increasing level of methane hazard.

The co-occurrence of the methane hazard and the spontaneous combustion of coal in the mining process depends on the mining and geological conditions in which the exploitation is carried out. The areas where these threats coexist are goaves, in which coal was left due to the mining process and where methane tends to accumulate. The pace and intensity of accumulation of these threats strongly depend on the ventilation system used for given longwall exploitation. All these factors indicate, which is also confirmed by the literature review, that determining dangerous zones in goaves is of key importance in case of the occurrence of both of these hazards.

Therefore, this paper deals with this subject by developing the methodology of applying model tests to determine dangerous zones in goaves due to these threats (Kuric, Klačková et al., 2022). The aim of the research, the results of which are presented in this paper, was to determine potential zones threatened by the spontaneous combustion of coal and methane explosions in goaves of a longwall ventilated with the Y system. The CFD technique and Ansys Fluent software were used for the research based on the finite volume method. The study was conducted for the area of the actual longwall in one of the hard coal mines in Poland. The developed methodology, based on the results of tests in real conditions (ventilation parameters, excavation geometry, geological structure), makes it possible to make a prognosis of the location of potentially dangerous zones for the Y-ventilation system (Kuric, Klačková et al., 2021). The results allow the design of appropriate prophylactic measures and their implementation as soon as the exploitation commences. Obviously, the effectiveness of the results will be verified on an ongoing basis, which will also influence the applied preventive measures. At the same time, this methodology, based on the results of model tests using real data concerning a given longwall and taking into account the simultaneous occurrence of two very dangerous natural hazards (methane and spontaneous combustion of coal), is a new approach to the issue under research (Tlach, Kuric et al., 2019). Until now, this extremely important and commonly occurring problem during underground exploitation has not been addressed.

First of all, the research fills the existing research gap in the field of determining the methane explosion hazard zone with a simultaneous threat of coal spontaneous combustion in goaves of a longwall ventilated with the Y-system. Secondly, the potential zones of occurrence of each of these hazards separately were determined for a particular longwall for the ventilation system under research, which gives many possibilities for conclusions regarding the applied prevention (Kuric, Tlach et al., 2020). The research was conducted for a spatial system, which is of fundamental importance for the analysis of point-like and volume methane accumulations. In the case of goaves, the commonly used methods of averaging results or reducing this issue to a two-dimensional problem do not work because the process of methane accumulation and self-heating of coal has a local, point-like character. Only a spatial analysis based on reliable data makes it possible to identify dangerous zones reliably.

An important advantage of this paper is the exact identification of dangerous zones and possibilities which the developed methodology has in the scope of predicting consequences related to not observing the rigours of exploitation in such unfavourable conditions as isolation of goaves, which should undoubtedly be the basis of undertaken preventive measures, also during the exploitation process. The developed methodology also enables current verification of the results and takes into account the new exploitation conditions that were not foreseen at the initial stage. This is also crucial due to the variability of the environment in which the process of underground mining is carried out.

Material and Methods

This section presents the studied longwall region and discusses the computational model used.

Area of research

The designed longwall B /11, which is 250 m long and 2.8 m high, is executed in the longitudinal system by breaking down the roof rock. The seam in which the longwall is run is classified in the 4th category of methane hazard, the 3rd group of coal susceptibility to spontaneous combustion and coal dust explosion class "B" (according to Polish regulations). This means that the coal bed has a methane-bearing capacity of more than 8 m3/Mg (ton) per pure coal and has an average propensity for spontaneous combustion.

The longwall is ventilated using the Y-type ventilation system with an additional supply of fresh air along the tailgate. Figure 1 presents a scheme of the longwall ventilation with marked directions of airflow.

Due to the magnitude of the methane hazard, approximately 1119.0 m^3/min of air will be supplied to the longwall via the main gate, while approximately 1029.0 m^3/min of air will be supplied to the longwall in the area of the longwall's intersection with this gate (longwall exit) via the tailgate.

Model tests of the airflow through the goaves of the longwall B/11 in the coal bed 358/1, which enable the determination of the methane explosion and coal spontaneous combustion danger zone in these goves, were carried out for the longwall length of 450.0 m.

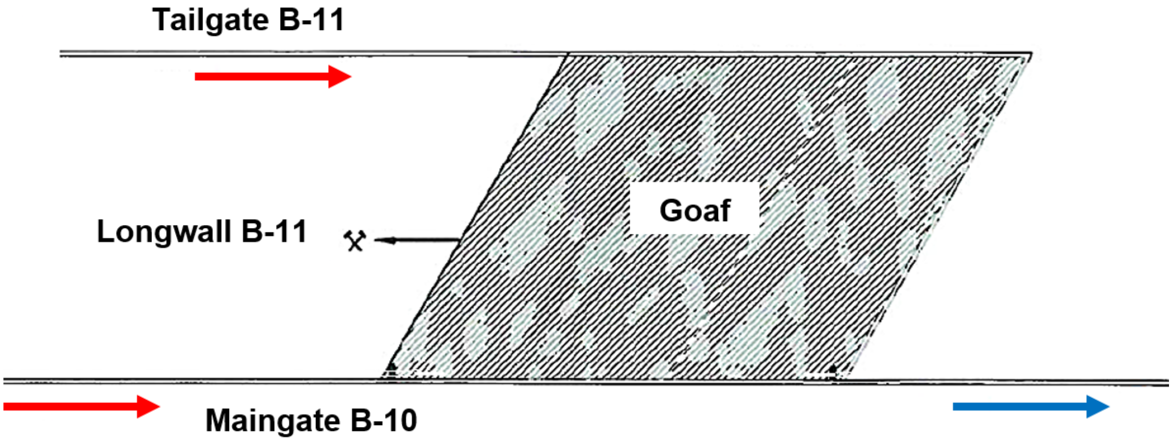


Fig. 1. Scheme of the area of studied longwall B /11 ventilated with Y system

Mathematical and Physical model of longwall and goaf

The aim of the conducted research was to identify zones in the goaves of the analyzed longwall that are potentially endangered by methane explosions and the spontaneous combustion of coal. In order to determine these zones, model tests were performed based on numerical simulations. Computational Fluid Dynamics (CFD) and the ANSYS Fluent software were used for this purpose. This program uses the Finite Volume Method to discretize a geometric model. The methodology involves the development of geometric, physical and mathematical models of the studied region. The adoption of boundary conditions precedes the discretization process, and then the calculations and analysis of results (post-processing) are performed. The following sections briefly discuss the most important stages of the developed research methodology.

Governing equations for a mathematical model of flow

The airflow through the longwall region, which includes longwall workings, a longwall and goaves, is described by a model consisting of the so-called controlling equations (Li et al., 2020; Kuznetsov and Nahornyi, 2020; Tutak et al., 2019; Yuan et al., 2022). The system of equations describing this flow includes:

– Mass conservation equation:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

– Momentum conservation equation (Navier – Stokes equation):

$$\begin{gathered}\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=\frac{\partial}{\partial x}\left(u\frac{(\partial u)}{\partial x}\right)+\frac{\partial}{\partial y}\left(u\frac{(\partial u)}{\partial y}\right)+\frac{\partial}{\partial z}\left(u\frac{(\partial u)}{\partial z}\right)-\frac{\partial p}{\partial x}+S_u\\ \frac{\partial(\rho vu)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=\frac{\partial}{\partial x}\left(u\frac{(\partial v)}{\partial x}\right)+\frac{\partial}{\partial y}\left(u\frac{(\partial v)}{\partial y}\right)+\frac{\partial}{\partial z}\left(u\frac{(\partial v)}{\partial z}\right)-\frac{\partial p}{\partial y}+Sv\\ \frac{\partial(\rho wu)}{\partial x}+\frac{\partial(\rho wv)}{\partial y}+\frac{\partial(\rho ww)}{\partial z}=\frac{\partial}{\partial x}\left(u\frac{(\partial w)}{\partial x}\right)+\frac{\partial}{\partial y}\left(u\frac{(\partial w)}{\partial y}\right)+\frac{\partial}{\partial z}\left(u\frac{(\partial w)}{\partial z}\right)-\frac{\partial p}{\partial z}+Sw\end{gathered} \tag{2}$$

– Energy equation:

$$\frac{\partial}{\partial t}\left(pc_pT\right)+\nabla\cdot\left(\rho c_pvT\right)=\nabla\cdot\vec{J}\cdot\left(k_{eff}+\frac{c_p\mu_t}{Pr_t}\right)\nabla T \tag{3}$$

– The turbulent kinetic energy transport equation:

$$\rho\frac{\partial k}{\partial t}+\frac{\partial}{\partial x_i}(\rho kv_i)=\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j})]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{4}$$

– The turbulent kinetic energy dissipation rate transport equation:

$$\begin{gathered}\rho\frac{\partial\varepsilon}{\partial t}+\frac{\partial}{\partial xi}(\rho\varepsilon v_i)=\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial\varepsilon}{\partial x_j})]+\\ C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon\rho}\frac{\varepsilon^2}{k}+S_\varepsilon\end{gathered} \tag{5}$$

– Equation of state for an ideal gas:

$$\rho=\frac{pM}{RT} \tag{6}$$

– Species transport equation:

$$\frac{\partial}{\partial t}(\rho Y_i)+\nabla\cdot(\rho\vec{v}Y_i)=\nabla\cdot\vec{J}_i+R_i+S_i \tag{7}$$

where:
$C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are the constants for *k-ε* turbulence model,
c_p is the specific heat of the gas,
G_b is turbulence depending on buoyancy,
G_k is the generic term for the turbulent kinetic energy *k* due to the average velocity gradient,
$\vec{J}_i$ is the diffusion flux of species *i*, kg/(m^{2}s),

k is turbulence kinetic energy (m^2/s^2),
k_{eff} is the effective gas thermal conductivity,
p is pressure (Pa),
P_{rt} is the turbulent Prandtl number,
R_i is the net rate of production of species i by chemical reaction,
S_i is the rate of creation by addition from the dispersed phase plus any user-defined sources,
S_k and S_ε are the user-defined source items,
T is the temperature (K),
v is the gas velocity (m/s),
Y_i is the local mass fraction of each species,
Y_M is the turbulence effect of compressibility,
ρ is the gas density (kg/m^3),
ε is the dissipation of turbulence kinetic energy (m^2/s^3),
τ is the viscous stress tensor (Pa),
μ_t is turbulent viscosity (Pa·s).

In the numerical simulations, goaves are treated as a continuous heterogeneous medium (i.e. porous, permeable medium). Therefore, the flow model is additionally described by the equation like the momentum loss source term of three-dimensional porous media:

$$S_i = -\left(\sum_{j=1}^{3} D_{ij} \mu v_j + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho v_i^2 \right) \tag{8}$$

where:
S_i is the loss source term for the i-th (x, y, or z) momentum equation**;**
v_j is the magnitude of the velocity;
Dij and Cij are the viscous resistance coefficient and inertial resistance coefficient.

Since goaves are treated as a porous medium, it is also necessary to determine their permeability. Permeability is the basic and key parameter for the analysis, which affects the gas distribution in a goaf. Goaf permeability is determined by the following relation (Szlązak and Szlązak, 2004):

$$k(x) = \frac{\mu_g}{r_0 + ax^2} \tag{9}$$

where:
$k(x)$ is the permeability of goaves (m^2);
μ_g is the coefficient of dynamic viscosity of air (Nsm^{-2}),
l is the total length of the longwalls (m),
r_0 is determined from the relation $r_0 = \frac{\mu}{k_0}$, and a is determined from the relation $a = 6 \cdot 10^9 R_{rrs}^{-1.74}$.

The coefficient k_0 is determined from the following equation:

$$k_0 = \frac{\mu_g}{6} \cdot 10^{-10} R_{rrs}^{1,44} \tag{10}$$

Physical model of goaf

The basic stage of the developed methodology was to prepare a numerical model for the longwall region. This area comprised goaves, a longwall, and longwall workings. The geometric model of the analyzed longwall is presented in Figure 2.

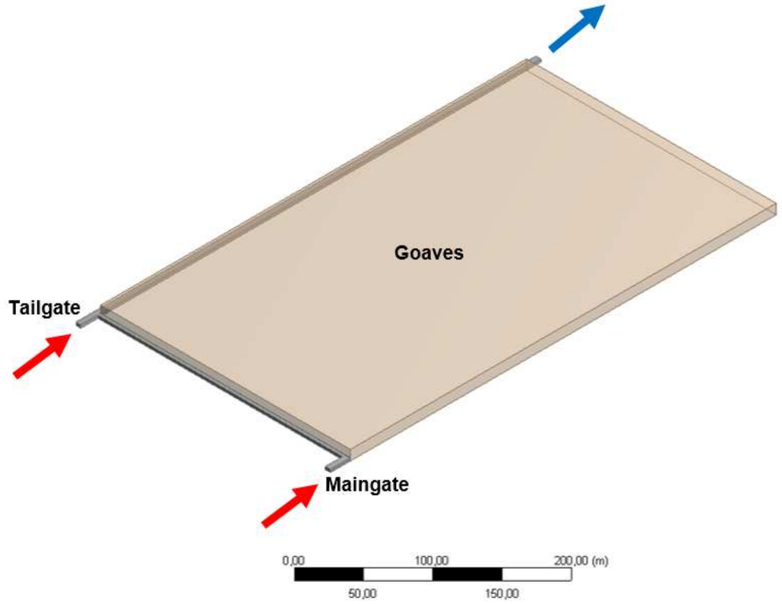


Fig. 2. Geometric models of longwall in numerical simulations

The geometric model of the examined longwall region ventilated with the "Y" system includes:

- a section of the maingate of 20.0 m length and cross-sectional area of A = 17.0 m^2,
- the tailgate maintained along the goaves with a length of 455.0 m,
- a section of the goaves with a length of 450.0 m.

The length of the longwall for each calculation variant was 250.0 m, and its height was 2.8 m. The vertical zone of airflow range in the goaves (goaf height) was 3.5 times the thickness of the exploited seam [ ]. Machinery and equipment used for longwall workings were not taken into consideration in the geometrical models (Klarák et al., 2022) The simplifications assumed in the models in relation to the real objects result from their size and constitute a certain compromise between the accuracy of calculations and the time needed to prepare the model and obtain a solution.

The geometric model developed in this way was subjected to a discretization process. The discretization of spatial geometric models resulted in generating a grid with control volumes. The generated grid for the geometric model of the studied region consisted of cubic and rectangular elements. The selection of the size of the numerical grid elements was preceded by an analysis of its sensitivity to the obtained calculation results. On the basis of this analysis, it was concluded that for the model tests of the airflow through the examined region, it was possible to adopt the structural numerical grid with cubic elements of 0.25 m x 0.25 m x 0.25 m for the longwall and longwall workings, and the structural numerical grid with cuboid elements of 0.25 m x 0.25 m x 0.5 m for the goaves. The total number of elements (control volumes) for the model prepared in this way was 11 394 570. The increased density of the numerical grid significantly increases the computation time, while there is no significant increase in the computation accuracy. The grid quality index is greater than 0.9, which means that the grid is at a good and acceptable level.

Figure 3 shows a fragment of the generated grid for the goaf model and the investigated workings.

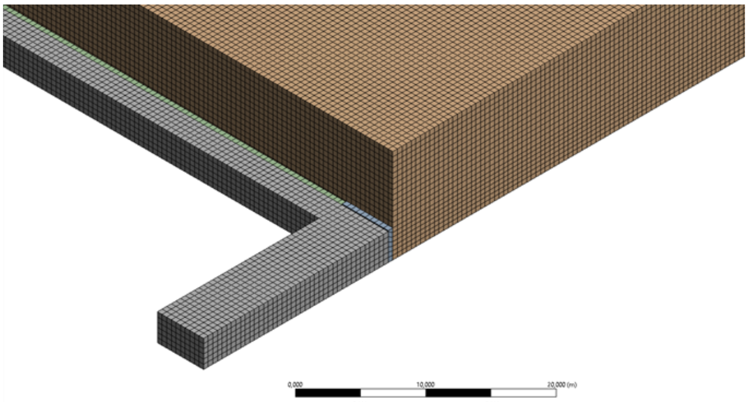


Fig. 3. A fragment of the discrete model of the studies region

The *k–ε* turbulent model in the standard variant and a model enabling the modelling of gas mixture flow (species transport) were used to analyze the air stream flow through the goaves of the longwall ventilated with the "Y" system with air discharge along the goaves. The SIMPLEC pressure velocity correlation algorithm was used for calculations. The second-order upwind algorithm was used to discretize the convection component of the momentum equation. The air volume flow rate supplied to the longwall via the Maingate was 1190 m^3/min, and the refreshing air flow rate supplied via the tailgate was 1029 m^3/min. It was assumed that the length of the gates amounting to 20.0 m would allow for the full development of the velocity profile.

For the analyzed models, a "pressure-outlet" boundary condition was defined in the tailgate. For the near-wall effects of the flow, standard functions and zero values of the flow velocity were assumed for the wall-type conditions (walls treated as excavation sidewalls), with surface roughness corresponding to a height of 0.1 m and temperature (treated as the temperature of the surrounding rock mass) – 40° C. The temperature of the air stream from the inlet to the workings was 20˚C (293.15 K).

Basic setups of the computational model are summarized in Table 1.

Tab. 1. Basic setups for the numerical simulations

Name	Initial conditions	Description
Ventilation mode		“Y”-type
Velocity inlet	Airflow volume rate (m^3)	1119.0
	Refreshing stream	1029
	Temperature of fresh air (K)	293.15
	Oxygen concentration in inlet airflow	20.9 %
	Hydraulic diameter (m)	3.6
	Atmospheric pressure (MPa)	0.1
Air	Air density (kg/m^3)	1.225
	Viscosity (Pa·s)	1.81×10^{-5}
Permeability	Permeability of goaf (m^2)	from 10^{-6} to 10^{-8}
General	Solver type	Pressure-based
	Time	Steady
Solution methods	Scheme	Coupled

The computational domain consisted of two parts, one of which was a representation of the longwall and longwall workings and the other of the goaves. In the goaf domain, a change in the permeability coefficient of these gaoves was defined as a function of the distance from the longwall face using the User Definition Function (UDF). This function was additionally defined in order to set a variable boundary condition, in this case, a variable permeability coefficient in the porous domain.

The developed model, along with the assumed unambiguity conditions, was subjected to numerical analysis. Its analysis enabled the determination of physical and chemical parameters of the air flowing through the goaves, which in turn helped to determine zones potentially endangered by methane explosions and the spontaneous combustion of coal.

Results and Discussion

The migration of air from a longwall to goaves, as well as air leaks caused by improperly made sealings and rock mass cracks caused by mining activities, are the main reasons for the inflow of fresh air rich in oxygen to goaves. On the one hand, this process dilutes methane present in goaves, and on the other hand, it stimulates the process of self-heating of coal, which leads to its self-ignition. When methane accumulates in goaves and reaches a concentration within the explosive limits, an explosion of this gas may occur, and the initiation of ignition may be the occurring process of self-heating of coal. That is why, on the basis of the results of the calculations carried out, potential zones were determined in goaves where:

- due to the risk of methane explosion, the concentration of this gas is within limits from 5 to 15%, and at the same time, the concentration of oxygen due to the explosiveness of methane is at least 12% (according to Coward's triangle);
- due to the threat of spontaneous combustion of coal, the speed of airflow through the goaf is from 0.2 to 0.0015 m/s, and the oxygen concentration is min. 8%;
- the concentration of methane is from 5 to 15%, the oxygen content min. 12%, and at the same time, a process of self-heating of coal may occur in it (in which the speed of airflow through the goaf is from 0.2 to 0.0015 m/s and the concentration of oxygen is min. 8%).

As a result of the analysis, the number of physical and chemical parameters were determined for the stream of air passing through the goaf of the longwall under investigation, which was ventilated with the Y system with refreshment via the tailgate along the coal body. Due to pressure differences in particular domains of the examined region, air migration to the goaf occurred, just as it does in reality. Since the longwall was ventilated with the Y-system, the inflow of air to the goaves took place from the side of the maingate and tailgate. As a result of this flow, the concentration of oxygen in the goaf decreases with increasing distance from the longwall face due to decreasing goaf permeability (goaf sealing), increasing methane concentration, and the process of coal oxidation taking place. In the case of applying the Y ventilation system with refreshment via the tailgate along the coal body, oxygen concentration distribution in the goaves is almost uniform at the tailgate and at the maingate. Figure 4 shows oxygen concentration distribution in the whole goaf, and Figure 5 shows the distribution of oxygen concentration above 12% (Figure 5a) and above 8% (Figure 5b).

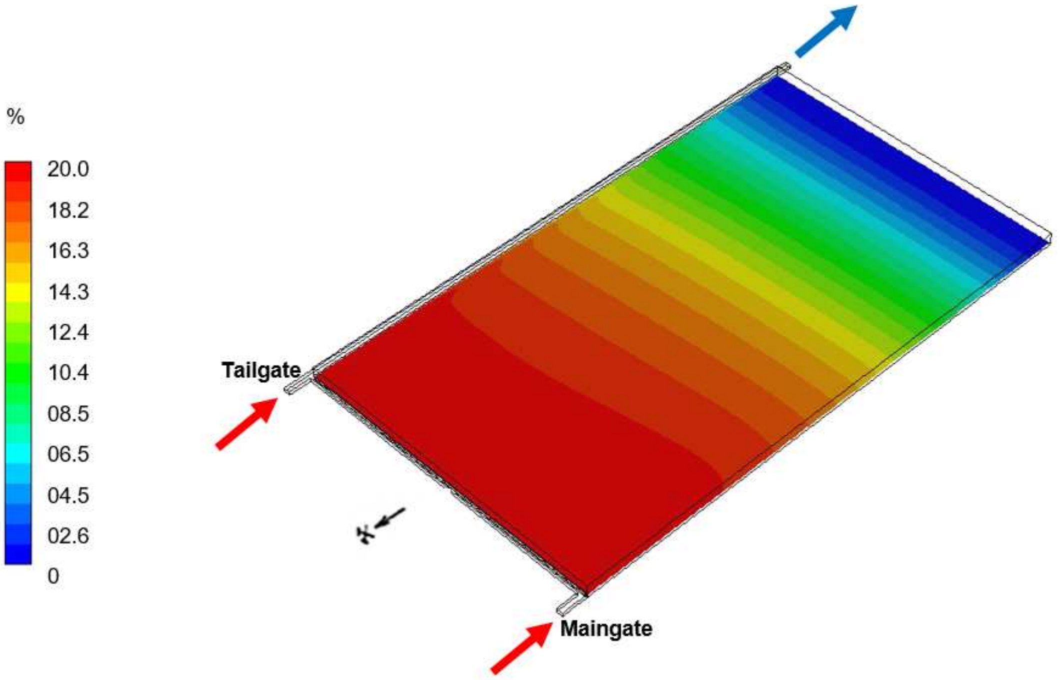
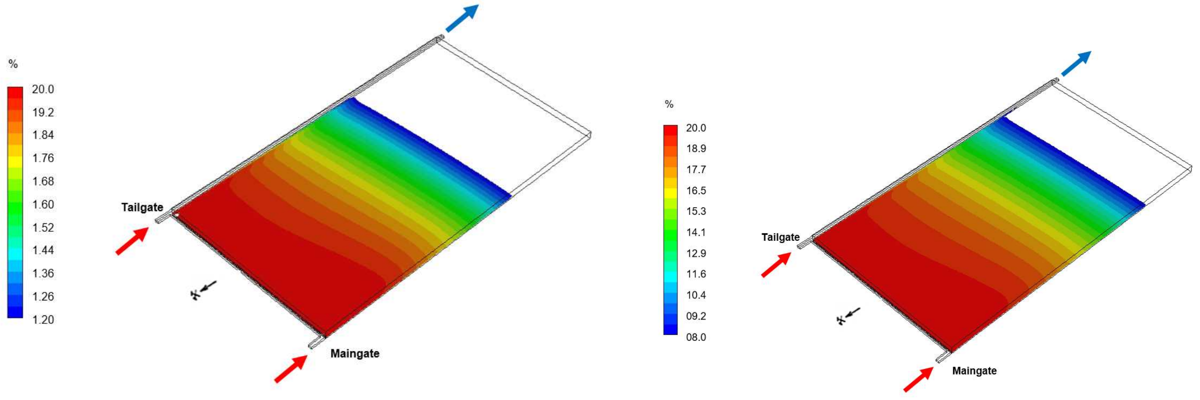


Fig. 4. Distribution of oxygen concentration in the goaves



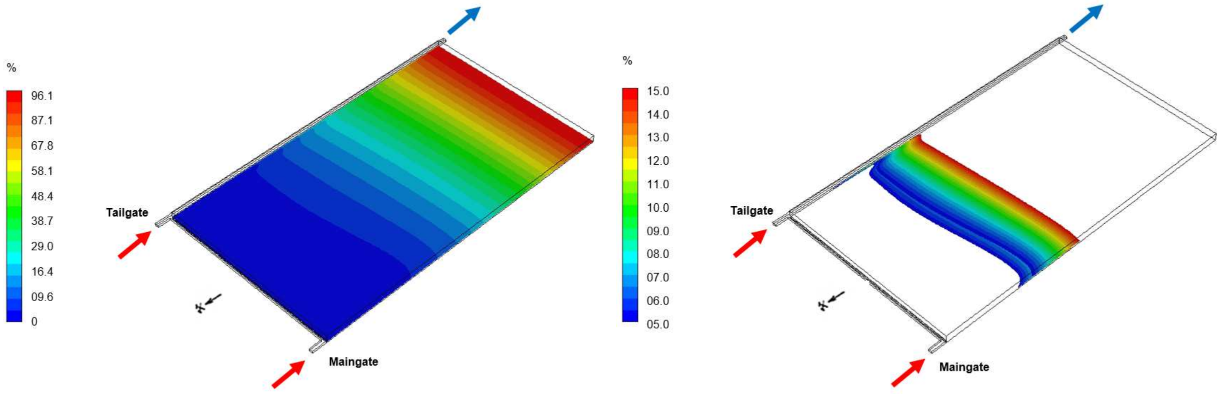
(a) **(b)**

Fig. 5. Oxygen concentration range in the goaves due to methane hazard – min. 12% (a) and oxygen concentration range necessary for self-heating process – min. 8% (b)

The conducted calculations showed that for the investigated ventilation system, the oxygen concentration in the goaves, in the whole goaf area, remained at a high level (Zajačko et al., 2018). High oxygen concentration in the goaves near the working space of the longwall was caused by the inflow of fresh air and low methane concentration, as well as by the low degree of sealing in this goaf region.

In the investigated case, the dangerous concentration of oxygen in the goaves due to the methane hazard (min. 12%) reached up to about 170 meters into their depths, while due to the threat of coal spontaneous combustion (min. 8%) – this range was up to about 215 m.

In the next stage, given the criteria of the methane explosion hazard, the distribution of the concentration of this gas within the whole goaf region was determined (Fig. 6a), as well as the concentration within the range of its explosiveness (Fig. 6b).



(a) **(b)**

Fig. 6. Distribution of methane concentration in the goaves (a) and the area of explosive methane concentration in these goaves (b)

The conducted calculations and distributions obtained on their basis showed that the low concentrations of methane occur behind the line of the longwall collapse, up to about 110 m of the goaf. High methane concentrations (not threatened with an explosion) occur in the rear part of the goaf from about 190 m. This means that the zone potentially endangered by the methane explosion is formed from about 110 m to 190 m of the goaf (Fig. 6b). However, since the oxygen concentration of min. 12% reaches only 170 m into the goaf (Fig. 5a), which means that the zone potentially endangered by the methane explosion has about 60 m in the goaf length and is shaped from 110 m to 170 m.

Figure 7 presents predicted methane and oxygen concentrations in the goaves of the analyzed longwall and the region in which an explosive atmosphere of this gas may potentially occur.

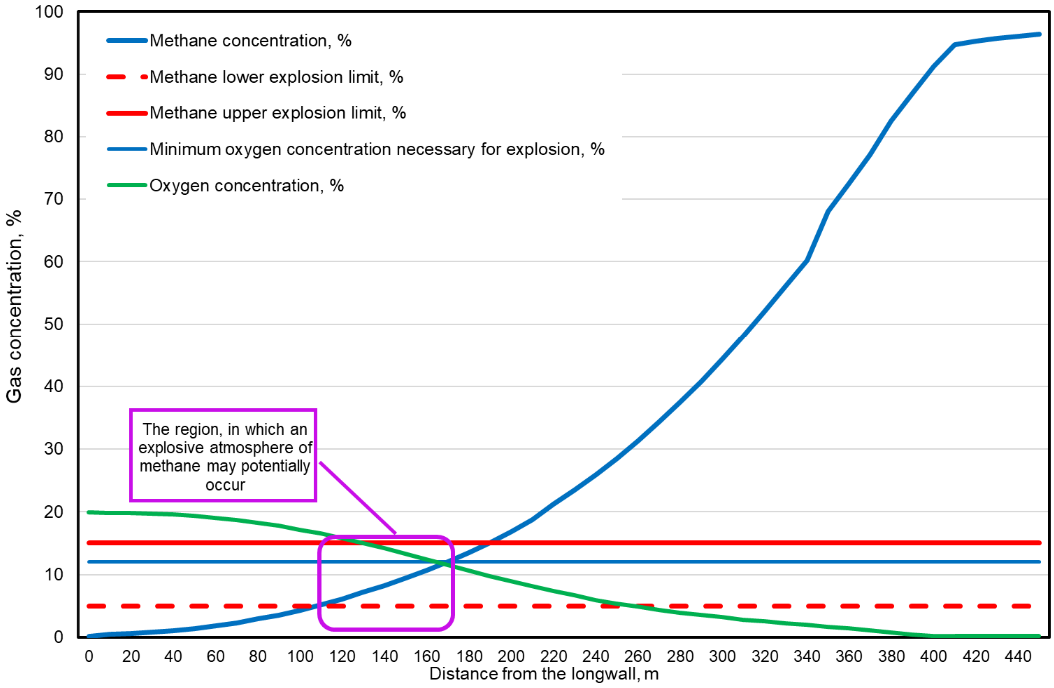


Fig. 7. Predicted concentrations of oxygen and methane in the longwall goaves and the zone of the potential risk of a methane explosion in these goaves

In the next stage of the research, the threat of spontaneous coal combustion was addressed.

In the longwall goaves, there is also a threat of coal spontaneous combustion, which can be a reason for methane explosion initiation, of course, if it occurs in the zone of its explosive concentration. That is why, from the point of view of mining safety, it is very important to determine the shape of the zone potentially endangered by an endogenic fire caused by the spontaneous combustion of coal.

The findings indicate that the oxygen concentration in which the coal oxidation process is possible (min. 8%) reaches 215 m into the goaf (Fig. 5b). A critical factor influencing the initiation and maintenance of the process of coal oxidation leading to its self-heating and consequently to self-ignition is appropriate to air velocity. This velocity must be between 0.02 and 0.0015 m/s (Tutak and Brodny, 2019). It may be noted that the flow of air with velocities falling in this range is able to reach deep into the goaves up to about 145 m, and slightly larger amounts of fresh air may penetrate deeper on the side of the tailgate (Fig. 8). This means that in almost half of the area of potential methane explosion hazard, there is also a factor that can initiate an explosion of this gas, namely the self-heating of coal. Figure 9 presents the forecasted concentration of oxygen in the goaves of the analyzed longwall and the velocity of air that passes through the goaves, as well as the area where the process of self-heating of coal, leading to its spontaneous combustion, may potentially occur.

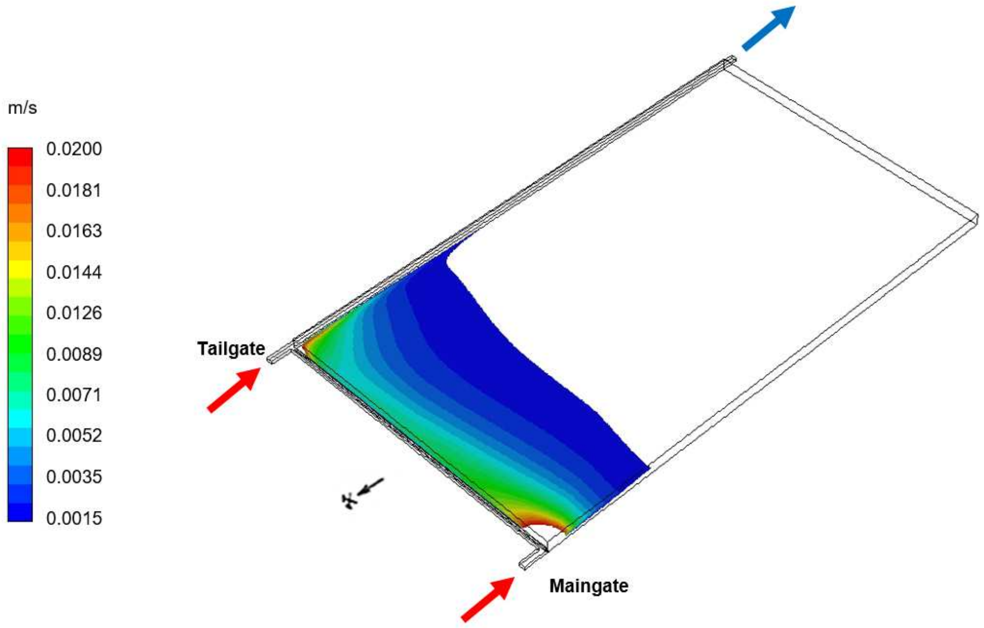


Fig. 8. Air velocity distribution in longwall goaves

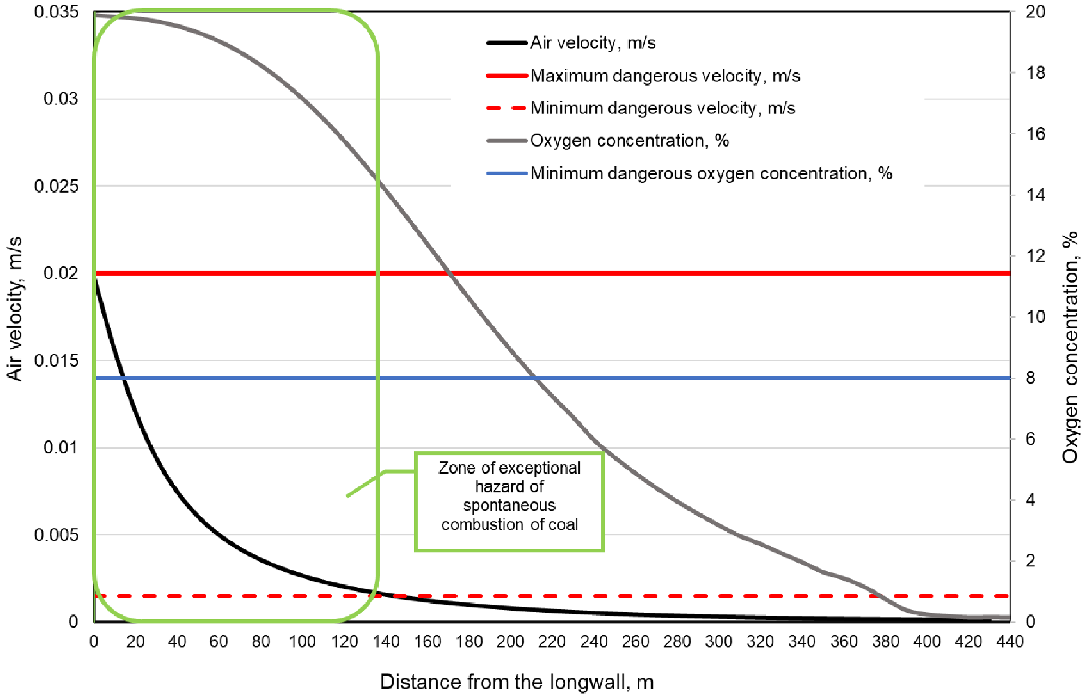


Fig. 9. Forecasted concentration of oxygen and air velocity in the goaves and the zone of the potential threat of coal spontaneous combustion in the goaves of the longwall under investigation

On the basis of the conducted research and the distribution of physical and chemical parameters of air flowing through the goaves of the longwall under investigation, it was found that the zone of the potential threat of spontaneous coal combustion is located just behind the longwall face, and its range deep into the goaf is approximately 145.0 m. This zone is an area where air velocity can cause heat accumulation in the oxidation zone (with an oxygen concentration of at least 8%). It can be concluded that in the goaf of this longwall, there is no cooling zone in which the air (just behind the mechanized casing along the whole length of the longwall) reaches a flow value greater than 0.02 m/s. This value is only exceeded in the upper and lower corners of the longwall (from the side of the air inlet to the goaves by means of the tailgate and maingate). Behind the zone of the potential occurrence of the threat of coal spontaneous combustion, at a distance of more than 145.0 m from the longwall face, a zone with insufficient air velocity but with a sufficient concentration of oxygen in the air is created due to this threat.

On the basis of the determined distributions of the velocity of air flowing through the goaves and the concentration of oxygen and methane, the zones of methane and coal spontaneous combustion hazards were determined, as well as the zone of methane explosion hazard caused by the spontaneous combustion of coal. The range of these zones is presented in Table 2.

The results unequivocally show that the most dangerous area in the goaf is the zone from 110 to 145 metres deep inside the goaf, measured from the side of the longwall.

Tab. 2. Summary of the locations of potentially dangerous zones in the goaves of the longwall under study

Hazard	**Zone of critical velocity of air flowing through the goaves**	**Zone of a critical concentration of oxygen in the air flowing through the goaves**	**Zone with explosive methane concentration**	**Potentially hazardous area**
in meters, (counted deep inside the goaf from the longwall side)				
Methane Hazard	N/A	(min. 12%) 0 –170.0 m	110-190 m	110-170
Coal spontaneous combustion	0-145.0 m	(min. 8%) 0 – 215.0 m	N/A	0-145.0
Methane explosion caused by spontaneous combustion of coal	-			110-145.0

Conclusions

Fires and/or methane explosions and the spontaneous combustion of coal are very common and extremely dangerous phenomena occurring in underground hard coal mining processes. These phenomena are reported in mines all over the world and pose a great threat to the safety and efficiency of these processes. In order to limit and eliminate the effects of these hazards, it is reasonable to determine potential zones of their occurrence. The use of model tests for this purpose creates great opportunities for multivariate research of this problem and support for actions improving the safety of exploitation. The conducted research and the obtained results can be the basis for preventive measures, the aim of which is to reduce methane and oxygen concentration (inerting) in endangered zones or to limit (or even cut off) air inflow to them (sealing of goaves).

The methodology developed and presented in this paper enables the prediction of the location of dangerous zones due to each of these hazards separately and due to their simultaneous occurrence. The application of model tests using CFD enables a very good representation of the examined area, including goaves and their variable permeability, which corresponds to real conditions. The Y ventilation system, which was adopted for the research, must also be checked in terms of the threat of coal spontaneous combustion. This is because it can provoke an endogenic fire through the oxygenation of the goaves, and then initiate a fire or a methane explosion.

Based on the results obtained, the following can be concluded:

- In the case of applying the Y ventilation system in a longwall with refreshment via a maingate along the body of coal, a high-velocity airflow in goaves (up to 0.0015 ms/) takes place on the length of up to 145 m deep inside these goaves. A higher airflow occurs at the goaf's periphery, on the side of air migration from longwall gates.
- High oxygen concentrations which enable the methane explosion (min. 12%) and coal self-heating (min. 8%) occur in a very large area of goaves: up to about 170 m – due to the methane explosion hazard and up to about 215 m – due to the coal self-ignition hazard.
- Explosive concentrations of methane (from 5% to 15%) remain in the goaf area from 110 m to 190 m of its depth.
- The potential methane explosion hazard zone covers an area from 110 m to 170 m deep inside goaves.
- A potential zone threatened by the spontaneous combustion of coal occupies an area of up to 145 m deep inside goaves.

- The potential zone of the methane explosion hazard caused by spontaneous coal combustion occupies an area from 110 m to 145 m in goaves.

The study resulted in determining zones in goaves potentially threatened by coal explosion and spontaneous combustion, as well as methane explosion due to a trigger caused by spontaneous coal combustion. On this basis, it was possible to direct preventive measures into strictly defined goaf zones, which reduced the possibility of dangerous events, and further reduced the cost of preventive measures. An important element in applying the developed method is the continuous monitoring of the ventilation parameters of the longwall region, where prophylaxis targeted at the zones determined based on model studies is adopted. The conducted research also clarifies how dangerous the spontaneous combustion of coal is from a physical perspective, which can trigger a fire and/or explosion of methane, which for obvious reasons, can be found in goaves.

The research methodology and the results presented in this article make it possible to precisely determine the location of zones where conditions necessary for fires and/or methane explosions and spontaneous coal combustion are met. The findings indicate that the application of model tests in combination with the results of tests in real conditions (used to determine boundary conditions for the model) can be successfully used for variant analyses of processes related to the ventilation of underground mine workings, as well as for analyses of emergency conditions. The application of the developed methodology should, therefore, considerably facilitate and reduce the costs of prophylactic measures aimed at improving mining safety.

It should also be stressed that the developed methodology is universal and may be applied for various geometric configurations of examined regions and for various physical and chemical parameters of air streams and ventilation systems.

References

Abd Ali, L.M., Ali, Q.A., Klačková, I., Issa, H.A., Yakimovich, B.A., Kuvshimov, V. (2021). Developing a thermal design for steam power plants by using concentrating solar power technologies for a clean environment. Acta Montanistica Slovaca, vol. 26 (4), 2021, pp. 773-783, 2021, DOI https://doi.org/10.46544/AMS.v26i4.14, 2021

Abramov, I., Bozek, P., Nikitin, Y., Abramov, A., Sosnovich, E., Stollmann. (2015). Diagnostics of electrical drives. In The 18th International Conference on Electrical Drives and Power Electronics . EDPE 2015. The High Tatras, Slovakia, 21 - 23. September 2015, pp. 364-367. DOI: 10.1109/EDPE.2015.7325321

Agboola, O., Babatunde, D., Fayomi, O., Sadiku, E., Popoola, P., Moropeng, L., Yahaya, A. and Mamudu, O. (2020). A review on the impact of mining operation: Monitoring, assessment and management. *Results in Engineering,* 8, 100181.

An, W., Li, Q., Liang, K., Yin, X. and Wang Z. (2021). Study on Combustion Characteristics and Evacuation during Intake Airway Fire in Coal Face under Different Ventilation Conditions. *Combustion Science and Technology*, 193, 1378-1399.

Brodny, J. and Tutak, M. (2022). Applying Sensor-Based Information Systems to Identify Unplanned Downtime in Mining Machinery Operation. *Sensors*, 22, 2127.

Brodny, J. and Tutak, M. (2016). Determination of the Zone Endangered by Methane Explosion in Goaf with Caving of Longwalls Ventilated on „Y" System. *Management Systems in Production Engineering*, 24, 247-251.

Burduk, A., Wiecek, D., Tlach, V., Ságová, Z., Kochanska, J. (2021). Risk assessment of horizontal transport system in a copper mine. Acta Montanistica Slovaca, vol. 26 (2), 2021, DOI 10.46544/AMS.v26i2.09, 2021

Cernecky, J., Valentova, K., Pivarciova, E., Bozek, P. (2015). Ionization impact on the air cleaning efficiency in the interior. In Measurement Science Review.Vol. 15, No. 4 (2015), online, pp. 156-166.

Cheng, L.H., Cao, D.Q. and Guo, H.M. (2021). Analysis of coal mine occupational disease hazard evaluation index based on AHP-DEMATEL. *Archives of Environmental & Occupational Health*, 76, 372-384.

Deng, J., Yang, Y., Zhang, Y.N., Liu, B. and Shu, C. (2018). Inhibiting effects of three commercial inhibitors in spontaneous coal combustion. *Energy* 160, 1174–1185.

Gao, A., Zhang, Q.L., Ma, D. and Li, L. (2021). Experimental Study on Gas Migration Laws at Return Air Side of Goaf under High-Temperature Conditions. *Combustion Science and Technology*, DOI: 10.1080/00102202.2021.2006650.

Gao, S., Gao, D., Liu, Y., Chai, J. and Chen, J. (2021). Distribution Law of Coal Spontaneous Combustion Hazard Area in Composite Goaf of Shallow Buried Close Distance Coal Seam Group. *Combustion Science and Technology*, DOI: 10.1080/00102202.2021.2007893.

Handrik, M., Kopas, P., Baniari, V., Vasko, M., Saga, M. (2017). Analysis of stress and strain of fatigue specimens localised in the cross-sectional area of the gauge section testing on bi-axial fatigue machine loaded in the high-cycle fatigue region. XXI Polish-Slovak Scientific Conference Machine Modeling and

Simulations MMS 2016, Hucisko, Poland, 6-8 sept. 2016, Procedia Engineering, vol. 177, pp. 516-519, DOI 10.1016/j.proeng.2017.02.254, 2017

Klarák, J., Andok, R., Hricko, J., Klačková, I., Tsai, H.-Y. (2022). Design of the Automated Calibration Process for an Experimental Laser Inspection Stand. Sensors 2022, 22, 5306, https://doi.org/10.3390/s22145306, 2022

Kopas, P., Blatnicky M., Saga M., Vasko, M. (2017). Identification of mechanical properties of weld joints of AlMgSi07.F25 Aluminium Alloy. Metalurgija, vol. 56 (1-2), 2017, pp. 99-102, 2017

Kopas, P., Saga, M., Baniari, V., Vasko, M., Handrik, M. (2017). A plastic strain and stress analysis of bending and torsion fatigue specimens in the low-cycle fatigue region using the finite element methods. XXI Polish-Slovak Scientific Conference Machine Modeling and Simulations MMS 2016, Hucisko, Poland, 6-8 sept. 2016, Procedia Engineering, vol. 177, pp. 526-531, DOI 10.1016/j.proeng.2017.02.256, 2017

Kovanič, Ľ.; Blistan, P.; Urban, R.; Štroner, M.; Blišťanová, M.; Bartoš, K.; Pukanská, K. Analysis of the Suitability of High-Resolution DEM Obtained Using ALS and UAS (SfM) for the Identification of Changes and Monitoring the Development of Selected Geohazards in the Alpine Environment—A Case Study in High Tatras, Slovakia. Remote Sens. 2020, 12, 3901, doi:10.3390/rs12233901.

Kovanič, Ľ. Possibilities of Terrestrial Laser Scanning Method in Monitoring of Shape Deformation in Mining Plants. Inżynieria Miner. J. Pol. Miner. Eng. Soc. 2013, 1, 29–41, ISSN 1640-4920.

Kuric, I., Klačková, I., Domnina, K., Stenchlák, V., Sága, M. jr. (2022). Implementation of Predictive Models in Industrial Machines with Proposed Automatic Adaptation Algorithm. Applied Sciences - Basel, Mdpi, 2022, vol. 12 (4), 1853, ISSN 2076-3417, DOI.org/10.3390/app12041853, 2022

Kuric, I., Klačková, I., Nikitin, Y.R., Zajačko, I., Císar, M., Tucki, K. (2021). Analysis of diagnostic methods and energy of production systems drives, Processes, Mdpi, 9, 843, DOI.org/10.3390/pr9050843, 2021

Kuric, I., Tlach, V., Císar, M., Ságová, Z., Zajačko, I. (2020). Examination of industrial robot performance parameters utilizing machine tool diagnostic methods. In International Journal of Advanced Robotic Systems, 17 (1), 2020, DOI 10.1177/1729881420905723, 2020

Kundu, S., Zanganeh, J. and Moghtaderi, B. (2016). A review on understanding explosions from methane air mixture. *Journal of Loss Prevention in the Process Industries*, 40, 507-523.

Kuznetsov, E. and Nahornyi, V. (2020). Gas flow simulation in the working gap of impulse gas-barrier face sea. *Management Systems in Production Engineering,* 28, 298-303.

Kwilinski, A. and Kuzior, A. (2020). Cognitive technologies in the management and formation of directions of the priority development of industrial enterprises. *Management Systems in Production Engineering,* 28, 133-138.

Li, L., Qin, B., Liu, J., Leong, Y-K., Li, W., Zeng, J., Ma, D. and Zhuo, H. (2021). Influence of airflow movement on methane migration in coal mine goafs with spontaneous coal combustion. *Process Safety and Environmental Protection*, 156, 405-416.

Li, L., Qin, B., Ma, D., Zhuo, H., Liang, H. and Gao, A. (2018). Unique spatial methane distribution caused by spontaneous coal combustion in coal mine goafs: An experimental study. *Process Safety and Environmental Protection*, 116, 199-207.

Li, T., Wu, B., Lei, B. and Huang, Q. (2020). Study on air leakage and gas distribution in goaf of Y-type ventilation system. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, DOI: 10.1080/15567036.2020.1768321.

Li, L., Qin, B.T., Liu, J.S. and Leong, Y.K. (2020). Integrated experimentation and modeling of the formation processes underlying coal combustion-triggered methane explosions in a mined-out area. *Energy*, 203, 11785.

Liu, W., Qin, Y.P., Hao, Y.J. and Gui, T.Z. (2013). Numerical simulation of spontaneous combustion in goaf under Y-type ventilation. *Liaoning Univ. Eng. Technol.*, 32, 874– 879.

Lu, X., Deng, J., Xiao, Y., Zhai, X., Wang, C. and Yi, X. (2022). Recent progress and perspective on thermal-kinetic, heat and mass transportation of coal spontaneous combustion hazard. *Fuel*, 308, 121234.

Onifade, M. and Genc, B. (2020). A review of research on spontaneous combustion of coal. *International Journal of Mining Science and Technology,* 30, 303-311.

Qiao, M., Ren, T., Roberts, J., Liu, H., Yang, X., Tan, L. and Wu, J. (2022). Improved computational fluid dynamics modelling of coal spontaneous combustion control and gas management. *Fuel,* 324, 124456.

Szlązak, J. and Szlązak, N. (2004). Numerical and mine research on airflow in goaf of longwalls. *Kwart. Gór. Geoinż.*, 3, 59–78.

Saga M., Blatnicka M., Blatnicky M., Dizo J., Gerlici J. (2020). Research of the Fatigue Life of Welded Joints of High Strength Steel S960 QL Created Using Laser and Electron Beams, Materials, vol.13 (11), Article No. 2539, DOI 10.3390/ma13112539, 2020

Saga M., Blatnicky M., Vasko M., Dizo J., Kopas P., Gerlici J. (2020). Experimental Determination of the Manson-Coffin Curves for an Original Unconventional Vehicle Frame. Materials, vol.13 (20), Article No. 4675, DOI 10.3390/ma13204675, 2020

Saga M., Jakubovicova L. (2014). Simulation of vertical vehicle non-stationary random vibrations considering various speeds, Scientific Journal of Silesian University of Technology-Series Transport. Vol. 84, pp. 113-118, 2014

Saga, M., Vasko, M. (2009). Stress sensitivity analysis of the beam and shell finite elements. Komunikacie, vol. 11 (2), pp 5-12, ISSN 1335-4205, 2009

Saga M., Vasko, M., Pechac, P.(2014). Chosen numerical algorithms for interval finite element analysis. Modelling of Mechanical and Mechatronic Systems, MMaMS 2014, Vysoké Tatry, Slovakia, 25-27 nov. 2014, Procedia Engineering, vol. 96, pp. 400-409, DOI 10.1016/j.proeng.2014.12.109, 2014

Sapietova, A., Saga, M., Novak, P., Bednar, R., Dizo, J. (2011). Design and Application of Multi-software Platform for Solving of Mechanical Multi-body System Problems. Mechatronics: Recent Technological and Scientific Advances. 9th International Conference on Mechatronics, Warsaw, Poland, sep. 21-24, 2011, pp. 345-354, 2011

Segota, SB., Andelic, N., Lorencin, I., Saga M., Car, Z. (2020). Path planning optimization of six-degree-of-freedom robotic manipulators using evolutionary algorithms. International journal of advanc*ed robotic systems, vol.17 (2)*, DOI 10.1177/1729881420908076, 2020

Tlach, V., Kuric, I., Ságová, Z., Zajačko, I. (2019). Collaborative assembly task realization using selected type of human-robot interaction. In; 13th International Scientific Conference on sustainable, modern and safe transport (Transcom 2019), Book Series Transportation Research Procedia, 40 (2019), DOI 10.1016/j.trpro.2019.07.078, 2019

Tutak, M., Brodny, J., Szurgacz, D., Sobik, L. and Zhironkin, S. (2020). The Impact of the Ventilation System on the Methane Release Hazard and Spontaneous Combustion of Coal in the Area of Exploitation—A Case Study. *Energies*,13, 4891.

Tutak, M. and Brodny, J. (2019). The Impact of the Strength of Roof Rocks on the Extent of the Zone with a High Risk of Spontaneous Coal Combustion for Fully Powered Longwalls Ventilated with the Y-Type System—A Case Study. *Appl. Sci*., 9, 5315.

Tutak, M., Brodny, J. and Navickas, K. (2019). Studying the Impact of the Location of Air-Duct Lines on Methane Distribution and Concentration in Dog Headings. *Acta Montanistica Slovaca*, 24, 285-295.

Urban, R., Štroner, M., Blistan, P., Kovanič, Ľ., Patera, M., Jacko, S., Ďuriška, I., Kelemen, M. and Szabo, S.(2019) The Suitability of UAS for Mass Movement Monitoring Caused by Torrential Rainfall—A Study on the Talus Cones in the Alpine Terrain in High Tatras, Slovakia, ISPRS International Journal of Geo-Information, 8(8), p. 317. doi: 10.3390/ijgi8080317.

Wiecek, D., Burduk, A., Kuric, I. (2019). The use of ANN in improving efficiency and ensuring the stability of the copper ore mining process. Acta Montanistica Slovaca, vol. 24 (1), pp. 1–14, 2019.

Yang, S., Hu, X., Liu, W., Cai, J. and Zhou, X. (2018). Spontaneous combustion influenced by surface methane drainage and its prediction by rescaled range analysis. *International Journal of Mining Science and Technology*, 28, 215-221.

Yuan, X., Xie, J., Gao, F. and Lian, Z. (2022). Assessment of shield support performance based on an innovative mathematical-physical model in longwall faces. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. doi:10.1177/09544062221091467.

Zajačko, I., Gál, T., Ságová, Z., Mateichyk, V., Wiecek, D. (2018) Application of artificial intelligence principles in mechanical engineering. In; Innovative technologies in Engineering production (ITEP´18), Book Series: MATEC Web of Conferences, Vol. 244, article no. 01027, 3rd International Scientific Conference on Innovative Technologies in Engineering Production (ITEP), 11-13 September 2018, Bojnice, Slovakia DOI 10.1051/matecconf/201824401027, 2018

Zawadzki, J., Fabijańczyk, P. and Badura, H. (2013). Estimation of methane content in coal mines using supplementary physical measurements and multivariable geostatistics. *International Journal of Coal Geology*, 118(1), 33-44.

Zhang, Y., Shao, W., Zhang, M., Li, H., Yin, S. and Xu, Y. (2016). Analysis 320 coal mine accidents using structural equation modeling with unsafe conditions of the rules and regulations as exogenous variables. *Accident Analysis & Prevention*, 92, 189-201.

Zhang, J., An, J., Wen, Z., Zhang, K., Pan, R. and Akter Al Mamun, N. (2020). Numerical investigation of coal self-heating in longwall goaf considering airflow leakage from mining induced crack. *Process Safety and Environmental Protection*, 134, 353-370.

Zhang, L., Wu, W., Bian, Y., Yang, M. and Luo, H. (2021). Influences of Gas Drainage Pipe Positions on Spontaneous Coal Combustion in the Gob: A Case Study of Baode Coal Mine in China. *Combustion Science and Technology*, DOI: 10.1080/00102202.2021.1925662.

Zhou, F.B., Shi, B.B., Liu, Y.K., Song, X., Cheng, J. and Hu, S. (2013). Coating material of air sealing in coal mine: clay composite slurry (CCS). *Appl. Clay Sci*. 80–81, 299–304.

Zhou, Z., Yang, Y., Zheng, K., Miao, H., Wang, M. and Li, P. (2020). Study on the Spontaneous Combustion Characteristics and Prevention Technology of Coal Seam in Overlying Close Goaf. *Combustion Science and Technology*. DOI: 10.1080/00102202.2020.1863953.

Zhu, H.Q., Liu, P.F. and Liu, X.K. (2011). The study of spontaneous combustion region partition and nitrogen injection effect forecast based on CFD method. *Proc. Eng*. 26, 281–288.

Zhu, P., Li,Q., Li, X., Zhang, G., Zhang, Y. and Zheng, Y. (2022). Investigation on the potential hazard zone of gas explosion in the goaf under longwall top caving coal mining condition. *Combustion Science and Technology*. DOI: 10.1080/00102202.2022.2027393.

Funding

This publication was funded by the statutory research performed at Silesian University of Technology, Department of Production Engineering, Faculty of Organization and Management, grant number BK-288/ROZ3/2022/(13/030/BK_22/0070).

This article is the result of the research project No. PBS3/B6/25/2015 ″Application of the Overall Equipment Effectiveness Method to Improve the Effectiveness of the Mechanized Longwall Systems′ Work in the Coal Exploitation Process”, realized in 2015-2018 and financed by NCBiR.