applied sciences

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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

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Received: 14 November 2019; Accepted: 3 December 2019; Published: 5 December 2019

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Abstract: During the ventilation of longwalls in hard coal mines, part of the air stream migrates to the goaves with caving. These goaves constitute a space (void) filled with rocks following coal extraction. In the case where these goaves contain coal susceptible to spontaneous combustion, the flow of such an air stream through the goaves may lead to the formation of favourable conditions for coal oxidation, self-heating and spontaneous combustion. Such an area is referred to as the zone with a particularly high risk of spontaneous coal combustion (endogenous fires). The location and extent of this zone depend on many factors, with one of the most important being the permeability of the goaves which determines the tensile strength of the roof rocks forming the caving. This strength determines the propensity of these rocks to transform into the state of caving and the degree of tightness of the cave-in rubble (treated as a porous medium). The purpose of the present paper is to determine how the tensile strength of roof rocks influences the extent of the zone with a particularly high risk of spontaneous coal combustion (endogenous fires) in caving goaves of the longwalls ventilated with the Y-type system. To achieve this goal, model-based tests were conducted for a region of the longwall mined with caving and ventilated with the Y-type system. Critical air speed and oxygen concentration values in the caving goaves of this longwall were determined for the actual conditions of exploitation. These parameters define the risk zone of spontaneous coal combustion. The tests also helped to determine the extent of this zone, depending on the strength of the rocks forming the caving. The results obtained unequivocally indicate that the type of rocks forming the caving affects its permeability and the extent of the risk zone for spontaneous coal combustion. At the same time, the distribution of this zone is substantially different than in the case of other ventilation systems. The results obtained are of real practical significance for preventive measures to reduce fire risks. The effectiveness of these measures significantly improves the safety of mining exploitation.

Keywords: numerical modeling; finite volumne method; underground coal mine; endogenous fires; spontaneous combustion; longwall; ventilation system

1. Introduction

There are various types of rocks forming the hard coal seams in Poland. They include claystones, coal shales, mudstones, sandstones and, where the ongoing exploitation is divided into layers, also hard coal. All of these rocks have different strength properties [1,2].

So far, the strength properties of the rocks surrounding mine headings have been considered primarily in terms of their impact on the capacity to maintain the stability of mine headings [3–5]. When coal is exploited with caving, the analysis also encompasses their capacity to transform into the state of caving and to maintain the roof in a longwall heading (classification by Salustowicz [6]). The strength properties of these rocks were, therefore, mainly examined in terms of rock mass mechanics.

From the perspective of ensuring safe exploitation in longwalls, the impact of the strength of roof rocks should be considered not only in terms of maintaining the stability of the mine headings, but also in terms of the occurrence of ventilation hazards, and—more precisely—the risk of spontaneous coal combustion (endogenous fires) in the caving goaves of longwalls.

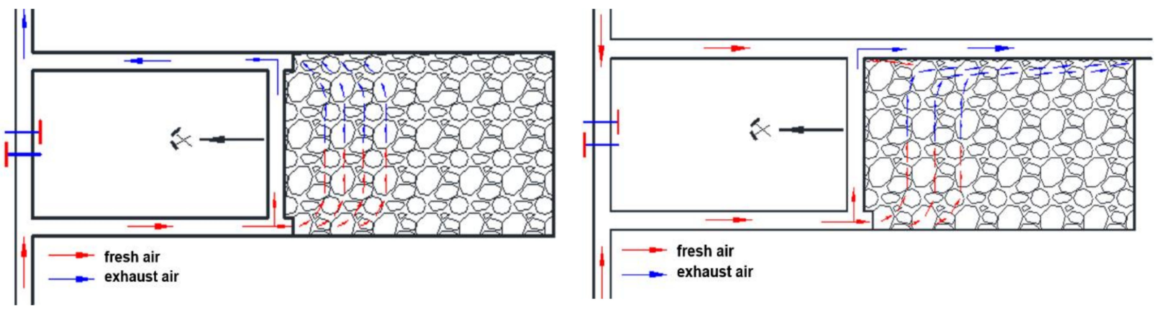
Spontaneous combustion of coal is a phenomenon that commonly occurs in hard coal mines [7–11]. It results from the self-ignition of coal following its self-heating in a mine heading or its immediate surrounding, e.g., in the goaves with caving.

Goaves with caving are a space formed after coal extraction, filled with rock rubble from the collapse of roof rocks hanging over the exploited seam. The degree to which this space is filled once the coal has been extracted depends on a number of factors. However, the most important of these is the type of roof rocks forming the goaves [12–14].

The parameter that is critical for the propensity of these rocks to transform into the state of caving is their tensile strength [15]. It determines the filling (tightness) degree of the cave-in rubble, and hence its porosity and permeability. Strong and solid roof rocks separating from the rock mass fill goaves with caving to a lesser extent than weak and brittle rocks. Therefore, goaves with caving filled with roof rocks of low tensile strength provide better filling of the space created after the mined coal (due to their lower permeability).

However, regardless of the type of rocks forming the goaves with caving, such goaves always include void spaces not filled with any rock material. These spaces, representing open contacts between chaotically arranged blocks of fractured roof rocks, form a particular type of a porous medium which allows for the flow of gases, including the air migrating from the longwalls.

The flow of air through goaves with caving results from its migration from the area of the longwall to which a stream of ventilation air is supplied. This stream is supplied to longwalls for their ventilation. There are several longwall ventilation systems, with the most common being the U-type ventilation system from the borders and the Y-type ventilation system [16] (Figure 1). Analysing both of these systems, it is possible to see a clear difference in the flow of air through the exploited headings.



(**a**) (**b**)

Figure 1. Diagram of the U-type (**a**) and Y-type ventilation systems (**b**).

The choice of a longwall ventilation system depends on a number of factors. The ventilation system must ensure proper chemical composition and temperature of the atmosphere [17–19]. One of the most important is the level of natural hazards, including gas-related risks, which occur in the region of active exploitation. In practice, there is no system that would be beneficial in the event of simultaneous occurrence of the self-combustion risk and the methane risk for the longwall under exploitation.

A system advantageous in the case of spontaneous combustion risk is less suitable for areas with methane hazard and vice versa. In longwalls with a high methane hazard which is typical of mines, it is increasingly common to use Y-type ventilation systems with air discharge along the goaves. However, this system is characterised by a significantly higher migration of air to the goaves with caving compared to the U-type ventilation system. This offers more favourable conditions for the self-heating of coal left in the goaves, which, in turn, may cause an endogenous fire to arise.

The research conducted by Szlązak [20] revealed that the total migration of air to the goaves with caving depending on the type of roof rocks filling the goaves with caving may, in extreme cases, amount to as much as approximately 40% (for rocks with the highest value of tensile strength).

The air stream migrating to the goaves with caving poses a risk for a low-temperature process of coal oxidation to be initiated, which may lead to spontaneous combustion of the coal left in the goaves. The prerequisites for this process to be initiated, besides the presence of coal, include the flow of air with a specific speed and appropriate oxygen concentration. When these conditions are met, it is possible for the reaction of low-temperature coal oxidation to be initiated, during which heat is produced and then accumulated by the coal, thereby causing its temperature to rise. If these conditions continue for a specific period of time (the incubation time), spontaneous combustion of coal, i.e., an endogenous fire, may occur.

The most essential factor affecting the process of heat accumulation is the speed of the air stream flowing through the goaves with caving in the longwall. This speed depends on the type of roof rocks forming the caving (since they influence their sealing degree) as well as on the volumetric flow rate of the air supplied to the longwall. However, the issue of how the volumetric flow rate of the air supplied to the longwall impacts the risk of endogenous fires has been discussed in several publications [21–24].

Nevertheless, no conclusive range has been determined for the air speed flowing through the goaves that would contribute to the initiation and maintenance of the coal oxidation process.

In the paper by Cheng et al., this value was assumed to range from 0.004 to 0.0016 m/s [21]. Chumak et al. [22], on the other hand, assumed that the critical speed value ranges from 0.015 to 0.0017 m/s, whereas Szlązak reported that this value is between 0.015 and 0.0015 m/s [23]. On the other hand, Wang et al. [24] indicated that this value ranges from 0.001 to 0.02 m/s. The speed ranges indicated are quite extensive. Therefore, the present paper assumes that this speed ranges from 0.02 m/s to 0.0015 m/s.

In the case of the oxygen concentration in the air flowing through goaves with caving, it has been demonstrated that the lower limit for self-combustion of coal is 8%. The results of the tests carried out by Buchwald [25] indicate that no spontaneous combustion of coal occurs below this value due to the insufficient concentration of oxygen.

Coal oxidation in the goaves with caving may occur only in the area of the goaves which meets both of the above conditions, namely the presence of crushed coal susceptible to spontaneous combustion and the air flowing through the goaves at a specific speed and with a specific oxygen concentration. This area could be termed as the zone with a particularly high risk of endogenous fires. In this zone, the physical and chemical parameters of the air reach values conducive to the initiation of the oxidation process.

This was used as the basis for formulating the risk criterion for spontaneous coal combustion (endogenous fire) in the goaves with caving, which includes:

- the presence of fragmented coal left in the goaves with caving.
- the speed of the air flowing through the goaves with caving must range from 0.0015 to 0.02 m/s.
- the level of oxygen concentration in the air flowing through the goaves with caving should be higher than 8%.

Works involving determination of the distribution of physical and chemical parameters of the air flowing through the goaves with caving have already been published. However, they only concerned the determination of speed distributions and oxygen concentrations in the goaves of longwalls ventilated with the U-type system [26–35]. These papers failed to take into account the type of roof rocks forming the goaves with caving, which affect their permeability, and hence the possibility of air to migrate inside the goaves, and the distributions of parameters.

One of the first papers dedicated to a three-dimensional analysis of air flow through the goaves of a longwall with caving was by T. Ren and R. Balusu [24]. In this paper, a spatial model was used to present the results of numerical tests concerning the distribution of oxygen concentration in the goaves of a longwall with caving after inertisation. The subsequent works of the same authors [27,28] also present the distribution of oxygen concentration in the goaves with caving. However, the determination of this distribution served as an introduction to numerical tests related to various methods for supplying an inert gas both into longwall headings and through the holes drilled from the surface.

On the other hand, Esterhuizen and Karacan [29], using their own model for determining the permeability of goaves with caving, carried out numerical research and determined the speed of the air flowing through the goaves. They concluded that this speed reaches the highest value at the borderline of the goaves (at the starting line of the longwall and behind the longwall lining).

For their own model-based tests, Yuan and Smith [30,31] used the permeability model of the goaves with caving, created by Esterhuizen and Karacan [29]. These tests were related to the self-heating of coal left in the goaves with caving and to the determination of the temperature in those goaves. The tests were based on chemical reactions during which heat is released into the atmosphere upon contact of coal with oxygen. This served as the basis for determining the dependency between the oxidation rate and temperature, and oxygen concentration.

Another work which attempted to examine the flow of air through a three-dimensional model of goaves with caving was the one by Dai et al. [32]. It presented the distributions of the air speed in the goaves of a longwall with caving ventilated by means of the U-type system at two different flow heights, namely 1.5 m and 3.0 m from the floor of the exploited seam. In this work, the dangerous speed value of the air flowing through the goaves with caving, conducive to the self-heating of coal, was assumed to be equal to 0.004 m/s.

Tests on the flow of air through goaves with caving of a longwall, using a three-dimensional model, were also carried out by Xie et al., who presented the results of such tests in the paper [30]. They built a numerical model reflecting a real-world longwall and goaves with caving. The tests they conducted helped them to determine the distribution of air speed in the goaves with caving and the distribution of air pressure.

On the other hand, Shi et al., in the paper [34], presented the results of model-based tests on the distribution of oxygen concentrations in the goaves of a longwall with caving. They conducted these tests on a three-dimensional model which made it possible to determine the distribution of oxygen concentration in the goaves with the values from 8% to 18%. This concentration poses a risk that the oxidation process of the coal left in the goaves with caving could be initiated.

On the other hand, Brodny and Tutak [35] determined the impact of the volumetric flow rate of the air stream supplied to the longwall on the speed of the air filtrating through goaves and on the concentration of oxygen in this air.

Analysing the papers published to date, it is possible to conclude that none of them has determined how the type of the roof rocks forming the goaves with caving impact the formation of the zone with a particularly high risk of spontaneous coal combustion. This zone has also not been considered in terms of the Y-type ventilation system.

Therefore, the Authors conducted model-based tests whose purpose was to determine the impact of the type of roof rocks forming the goaves with caving on the formation of the zone with a particularly high risk of spontaneous combustion of the coal left in the goaves of longwalls ventilated with the Y-type system.

It is practically impossible to determine the zone with a particularly high risk of spontaneous coal combustion in real-world conditions because this zone is formed in an inaccessible area of the goaves. The attempts to measure the ventilation parameters in the goaves made to date have been unsuccessful in the majority of cases. For this reason, this zone was demarcated using model-based tests, which are successfully used for variant analyses of the processes related to ventilation of underground mine headings, as well as for analyses of emergency states occurring in these headings [36–38].

The tests were conducted for the actual layout of headings in one of the longwalls of a hard coal mine. The tests were based on the geometry of this longwall and the ventilation parameters registered during its exploitation. The tests (boreholes in the roof) also helped to define the strength parameters of the roof rocks forming the caving.

The main purpose of the works performed was to develop a methodology of model-based tests for spatial analysis of the ventilation phenomenon related to the identification of the area in the goaves with caving, where it is possible for spontaneous coal combustion, i.e., an endogenous fire, to occur.

In order to specify the impact of the type of roof rocks forming the goaves with caving on the location and extent of the zone with a particularly high risk of spontaneous coal combustion in the goaves, additional analyses were also conducted for five different tensile strengths of the rocks. The analysis was based on the geometry and ventilation parameters of the longwall in question. A total of six variants were considered for the tensile strength of roof rocks, and the dependency between this strength and the zone with a particularly high risk of spontaneous coal combustion in the goaves were determined.

2. Materials and Methods

2.1. The Porosity and Permeability of Goaves with Caving

One of the most important properties of roof rocks determining their ability to transform into caving is the tensile strength. This strength is the natural ability of the rock mass to resist stratification and caving of the roof rocks into the space (void) left after the mined coal as a result of vertical forces [39,40].

The value of the tensile strength of the roof rocks is determined by means of a down-hole penetrometer or the direct method—by stretching the sections of the vertical core of the borehole in the direction of the longitudinal axis of the borehole, and then it is determined from the following relationship:

$$R_{rri} = 0.8\frac{F}{d^2} \tag{1}$$

where R_{rri} is tensile strength of the rocks (Pa), F is the applied axial load (N) and d is core diameter (m^2).

This value depends on the type of roof rocks forming the caving. The maximum value of the tensile strength of rocks in Polish mines amounts to approximately 8 MPa [1,2]. In practice, however, such value is rare. Table 1 presents the types of roof rocks and the values of their tensile strength, as well as the characteristics of the roofs formed by these rocks.

Table 1. The types of roof rocks and the values of their tensile strength (own study based on [1,2]).

Tensile Strength of Roof Rock, R_{rrs}, MPa	Description of Roof	Example of Rock
0–0.5	Roof falling immediately after unveiling	clay and sandy slates, coals
0.5–1.5	Falling roof (clay and sandy slates) and weakly self-supporting (coal)	clay and sandy slates, coals
1.5–3.0	Cracked roof, partially self-supporting and bearing, easily passing into a caving state	shales, sandy shale, coals
3.0–4.5	Self-supporting roof, it goes automatically into a caving state without sagging into goaves	coarse-grained sandstones
4.5–6.0	Supporting roof, without roof falls, hardly passing into caving state, sagging into goaves	sandstones (medium)
➢ 6.0	Strongly compacted roof, very difficult for passing into caving state	sandstones (hard)

After such calculation of the tensile strength of roof rocks, it is possible to determine the permeability coefficient of goaves with caving, using the following equation [41]:

$$k(x) = \frac{\mu_g}{r_0 + ax^2} \text{ for } 0 \leq x \leq 2/3 \cdot l \tag{2}$$

as well as the equation:

$$k(x) = \frac{\mu_g}{r_0 + a\left(\frac{4}{3}l - x\right)^2} \text{ for } 2/3 \cdot l \leq x \leq l \tag{3}$$

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

The value of the permeability coefficient of caving goaves k_0 behind the front of the longwall is determined from the following equation [41]:

$$k_0 = \frac{\mu_g}{6} \cdot 10^{-10} R_{rrs}{}^{1,44} \tag{4}$$

The porosity of goaves varies on the basis of "O-zone theory" [42]. The porosity distribution along the strike direction in the middle of the working face goaves is determined from the following equation [41]:

$$n_x = 0.2e^{-0.0223x} + 0.1 \tag{5}$$

where n_x is the porosity distribution along the middle line of working face of longwall in goaves (%); x is the x position of the goaves (m).

The porosity of goaves in dip distribution can be determined from the following equation [43]:

$$n_y = e^{-0.015y} + 1 \text{ for } 0 < y < \frac{L}{2} \tag{6}$$

$$n_y = e^{-0.015(L-y)} + 1 \text{ for } \frac{L}{2} < y < L \tag{7}$$

where n_y is the porosity distribution along dip direction (%), y is the y position of the goaves (m); L is the length of the working face of longwall (m).

2.2. Methods

The objective of the tests conducted was to determine the impact of the type of roof rocks forming the goaves with caving on the extent of the zone with a particularly high risk of spontaneous combustion of coal in the goaves of a longwall ventilated with the Y-type system.

The analyses were conducted for a spatial model representing a real-world longwall along with longwall headings and goaves with caving, making use of Computational Fluid Dynamics (CFD). The Authors' experiences and the results obtained by other researchers indicate that this method may be used successfully for such analyses of the phenomena related with the flow of gases and the transfer of mass and heat [44].

The analyses were carried out by means of the ANSYS Fluent 18.2 commercial software. This software uses the finite volume method (FVM) for discretisation of the geometric model. The methodology for conducting tests by means of this programme involves development of a geometric model, a discrete model and a mathematical model of the phenomenon in question, as well as adoption of boundary conditions, performance of calculations and analysis of the results obtained. The most important stages of the methodology for the tests conducted are briefly discussed in the subsequent chapters of the article.

In the case at hand, this methodology is also supplemented with tests in real-world (actual) conditions. This is because the results of these tests serve as the basis for developing a geometric model for the region under analysis and for adopting the boundary conditions. The process of analysing the results of model-based tests also involves their verification with reference to real-world conditions.

2.2.1. Mathematical Models

The flow of air stream through the longwall and the longwall headings is deemed to be of a turbulent nature, while the flow of air stream through the goaves with caving of a laminar nature.

The mathematical mapping of a model of a longwall region and the goaves with caving takes the form of a set of equations which describe the aforementioned types of flows. These equations describe the flow of the mixture of air and mining gases released from the rock mass and generated as a result of the ongoing mining operations. Examining the three-dimensional flow of the air stream through region under analysis, encompassing the flow through the longwall, longwall headings and goaves with caving, one must consider the analytical models describing a turbulent and laminar flow towards the component parts of the Cartesian x, y and z coordinate system, in the particular calculation domains of the model. Modelling the flow of a multi-component mixture also requires solving additional equations for the transportation of the mixture components.

Basic Flow Equations

The flow of the air stream mixture is described by means of constitutive equations, which include the equations of mass, momentum and energy conservation and species transport equation. Conservation equations for mass, momentum, and species can be expressed as [45]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \boldsymbol{v} = 0 \tag{8}$$

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot \rho \boldsymbol{v}\boldsymbol{v} = -\nabla p \cdot \nabla \boldsymbol{\tau} + \rho \boldsymbol{g} \tag{9}$$

$$\frac{\partial}{\partial t}\left(p c_p T\right) + \nabla \cdot \left(\rho c_p \boldsymbol{v} T\right) = \nabla \cdot \left(k_{eff} + \frac{c_p \mu_t}{Pr_t}\right) \nabla T \tag{10}$$

$$\frac{\partial}{\partial t}(\rho \varpi_i) + \nabla \cdot (\rho \varpi_i \boldsymbol{U}) = \nabla \cdot \left(\rho D_{i,eff} + \frac{\mu_t}{Sc_t}\right) \nabla \varpi_i \tag{11}$$

where: ρ is the gas density (kg/m^3), $\boldsymbol{v}$ is the gas velocity (m/s), p is pressure (Pa), $\boldsymbol{\tau}$ is the viscous stress tensor (Pa), $\boldsymbol{g}$ is gravity acceleration (m·s^{-2}), c_p is the specific heat of the gas, k_{eff} is the effective gas thermal conductivity, T is the temperature (K), ω_i is the mass fraction of species i (N_2, O_2 and CH_4), μ_t is turbulent viscosity (Pa·s), $D_{i,eff}$ is the effective diffusivity of species i (m^2/s), Sc_t is the turbulent Schmidt number (0.7) and Pr_t is the turbulent Prandtl number.

Turbulence Model

The stream of the air and methane mixture flowing through the longwall and longwall headings, as well as through the initial section of the goaves with caving, is of a turbulent nature.

The analyses related to the flow of gas mixtures, including air, use the Reynolds number as the criterion specifying the type of flow, whose critical value makes it possible to determine the critical state of the flow separating the area of static laminar flow from the turbulent flow.

Therefore, by taking a time average of the Navier–Stokes equations, the Reynolds-averaged Navier–Stokes (RANS) equations have the following form [46]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_i)}{\partial x_i} = 0 \tag{12}$$

$$\frac{\partial(\rho v_i)}{\partial t} + \frac{\partial\left(\rho v_i v_j\right)}{\partial x_j} = -\frac{\partial}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial v_l}{\partial u_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\overline{\rho v'_i v'_j}\right) \quad (13)$$

As can be seen from Equation (11), a new variable, the Reynolds stress $\overline{\rho v'_i v'_j}$ is introduced to the equations and it must be solved to achieve the closure of the equations. Two approaches are adopted to calculate the Reynolds stress, i.e., the Reynolds stress models (RSM) and the Boussinesq hypothesis. The Reynolds stresses are related to the mean velocity gradients in the Boussinesq hypothesis [46]:

$$-\ \overline{\rho v'_i v'_j} = \mu_t\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t \frac{\partial v}{\partial x_k}\right)\delta_{ij} \quad (14)$$

In the turbulence model $k - \varepsilon$, in the standard variation, the basic Navier–Stokes equation has been transformed into the Reynolds averaged equation. This equation includes an additional term in the form of the Reynolds stress tensor. Due to this term, the set of equations is not closed. To close the set of equations, it is necessary to introduce additional differential equations, which include the equation of kinetic turbulent energy and the equation of kinetic turbulent energy dissipation in the following form [46]:

$$\rho\frac{\partial k}{\partial t} + \frac{\partial}{\partial x_i}(\rho k v_i) = \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j})] + G_k + G_b - \rho\varepsilon - Y_M + S_k \quad (15)$$

$$\rho\frac{\partial \varepsilon}{\partial t} + \frac{\partial}{\partial xi}(\rho \varepsilon v_i) = \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j})] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon\rho}\frac{\varepsilon^2}{k} + S_\varepsilon \quad (16)$$

where: $C_{1\varepsilon}$, $C_{2\varepsilon\rho}$, $C_{3\varepsilon}$ are constans, σ_k, σ_ε are turbulent Prandtl numbers for k and ε, G_b is the generation of turbulence kinetic energy due to buoyancy, G_k is the generation of turbulence kinetic energy due to the mean velocity gradients, Y_M is contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, S_k, S_ε are user-defined source terms.

In the Ansys Fluent software, the porous medium (the goaves with caving) is represented as a fluid characterised by two additional parameters. These parameters include porosity and the permeability coefficient. In order for the tests to take into account the porous medium through which the flow occurs, it is required to consider the source term S_i in the equation of momentum preservation. The additional source term assumes the following form [46]:

$$S_i = -\left(\sum_{j=1}^{3} K_{ij}\mu u_i + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho v_i^2\right) \quad (17)$$

where S_i is the pressure loss items defined by Darcy's law and C_2 is the inertial resistance factor.

2.3. Problem Statement and Boundary Conditions

The basis stage of the tests conducted was to develop a numerical model for the real-world (actual) region of the longwall under analysis. This area covers the goaves with caving, the longwall and the longwall headings. The actual tensile strength of the roof rocks forming the caving in this longwall amounted to 3.06 MPa. Additionally, tests were also conducted for the following strength values of these rocks: 2, 4, 5, 6 and 7 MPa.

The geometric parameters of the entire region under analysis were taken into consideration during the development of the model. The geometric model of the longwall under analysis, ventilated with the Y-type system along with the equivalence conditions adopted, is presented in Figure 2.

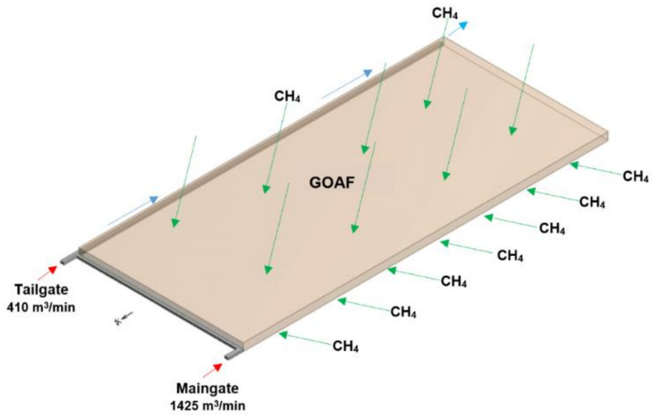


Figure 2. The geometric model with the assumed equivalence conditions for the longwall under analysis ventilated with the Y-type system.

The geometric model of the longwall area investigated takes into account the following:

- a section of the longwall gallery with a length of 20.0 m and a cross sectional area of A = 15.0 m^2.
- a tailgate maintained along the goaves with caving, with a length 525.0 m.
- a longwall with a height of 3.0 m and a length of 220.0 m, and an inclination of 0°.
- a section of goaves with caving with a length 500.0 m (constituting 2/3 of the longwall panel length).

In order to examine the air flow through the caving goaves of longwalls, it was also necessary to determine the vertical extent of this flow. Generally, it is assumed that the zone of air flow through the goaves with caving is equal to three to four times the thickness of the exploited seam (layer) [36].

The height of this flow is determined by the extent of the full caving and is equal to three times the thickness of the exploited layer. Taking into consideration the fact that the air also flows in the space (void) of the mined longwall, we obtain a flow zone measuring four times the thickness of the seam. On the other hand, taking into account the settlement of the basic roof by a value of 0.5 ÷ 0.6 of the seam thickness, it was assumed that the height of the air flow in the goaves amounts to 3.5 times the thickness of the exploited seam (layer).

Such geometrical models were subjected to the process of discretization. The selection of the right size of the numerical mesh elements was preceded by an analysis of its sensitivity to the calculation results obtained. Based on the analysis, it was concluded that, for model-based tests of air flow through goaves with caving, one may adopt a structural numerical mesh with the size of cubic elements equal to 0.05 m × 0.05 m × 0.05 m for a longwall and longwall headings, as well as a structural numerical mesh consisting of cuboidal elements (type of mesh: hexahedron) measuring 0.025 m × 0.025 m × 0.025 m for goaves with caving. Smaller elements significantly extend the time of calculations, without making any changes in the results obtained.

The "inlet" and "outlet" boundary conditions were defined in longwall galleries. The "inlet" boundary condition was set in the distance of 20.0 m from the longwall, in the maingate as well as in the tailgate. It was assumed that the length of longwall galleries amounting to 20.0 m would allow for full development of the speed profile for the air stream supplied to the longwall.

The volumetric flow rate of the air supplied to the longwall under analysis was equal to 14,250 m^3/min. The volumetric flow rate of the air supplied through the tailgate amounted to 410 m^3/min.

The "outlet" boundary condition (pressure-outlet) was defined in the tailgate (this reflects the actual condition in the longwall region).

For longwall-related interactions of the flow, standard functions and zero values were adopted for the flow speed in "wall-type" conditions (longwalls treated as the sidewalls of headings), whose surface roughness corresponded to the height of 0.1 m, and their temperature (treated as the temperature of the surrounding rock mass) amounted to 40 °C. The temperature of the air stream at the inlet to the headings was 23 °C. The oxygen concentration in the air stream at the inlet to the headings was assumed to be equal to 20.8% (the value registered by automatic gasometry sensors, oxygen metres).

The analysed systems of headings took into consideration the flow of methane in the goaves with caving, which was equal to 8 m^3/min (according to actual measurements).

The computational domain consisted of two parts, with one mapping the longwall and longwall headings and the other the goaves with caving. In the domain reflecting the goaves with caving, a definition was provided for a change in the permeability coefficient of the goaves with caving as a function of distance from the longwall front, by means of the created user definition function (*UDF*).

The geometrical models failed to incorporate the machinery and devices forming the equipment of longwall headings.

The simplifications adopted in the models developed, in relation to the real-world (actual) objects, arise out of their sizes and constitute a certain compromise between calculation precision and the time of finding a solution.

The ANSYS Fluent 18.2 software was employed for all numerical simulations. The pressure–velocity coupling and scheme-coupled algorithm, the second-order upwind discretization method and the algebraic multigrid method were used to solve the equation.

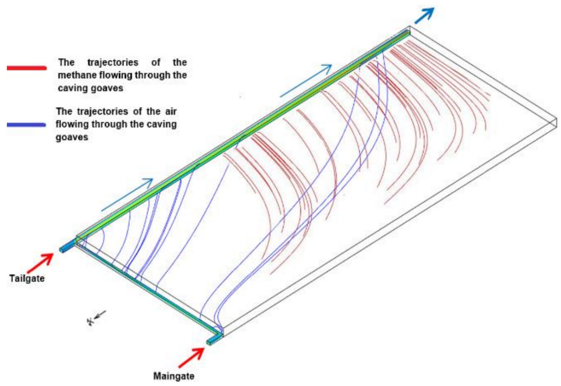
Such models, along with the adopted conditions of uniqueness, were subjected to numerical analysis.

The each calculation required approximately 1500–1800 iterations, with a convergence tolerance of 10^{-6} for all variables (as per the "Fluent Theory Guide" support documentation).

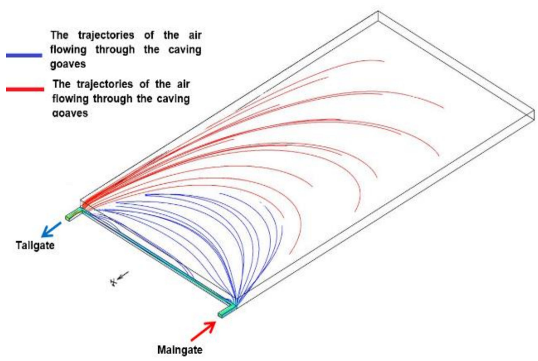
3. Results and Discussion

The analyses conducted helped to determine a series of physical and chemical parameters of the air stream and methane flowing through the region under investigation.

In order to illustrate the processes related to this flow, Figure 3 shows the trajectories of the mixture of air and methane flowing through the caving goaves of the longwall ventilated with the Y-type system with the air being discharged along the goaves. A preliminary analysis of the distribution obtained was enough to demonstrate its great difference from the distributions concerning, for instance, the U-type ventilation system.



(**a**)



(**b**)

Figure 3. The trajectories of the mixture of air and methane flowing through the goaves with caving for Y-type ventilation system (**a**) and U-type ventilation system (**b**).

Figures 4–15 present the results of the analysis for the goaves with caving formed by roof rocks whose tensile strength is equal to 3.06 MPa (as is the case in a real-world system).

Figures 4–6 present, respectively, the distributions of the air speed and the dangerous speed due to the risk of endogenous fires, as well as the oxygen concentration levels in the goaves with caving at a distance of 0.5 m from the floor of the exploited seam.

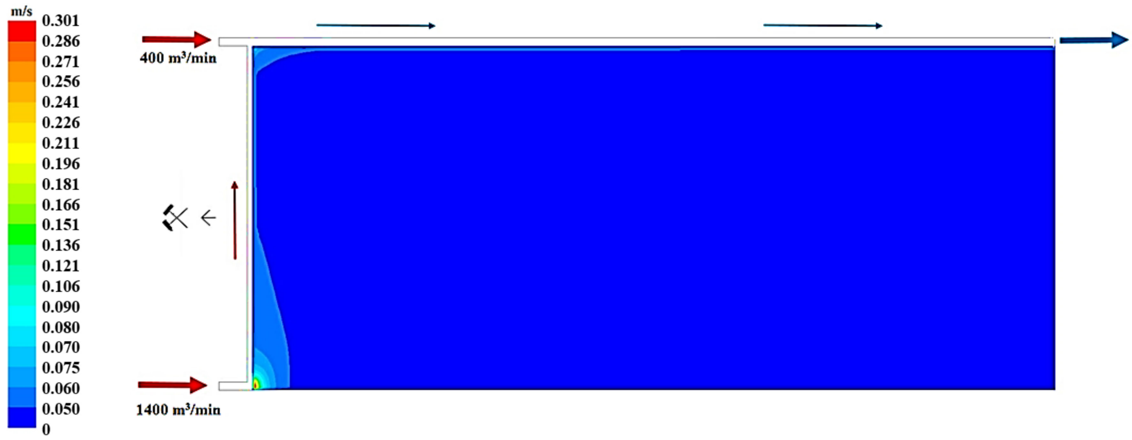


Figure 4. The distribution of the air speed flowing through the goaves with caving at a distance of 0.5 m from the floor of the exploited seam.

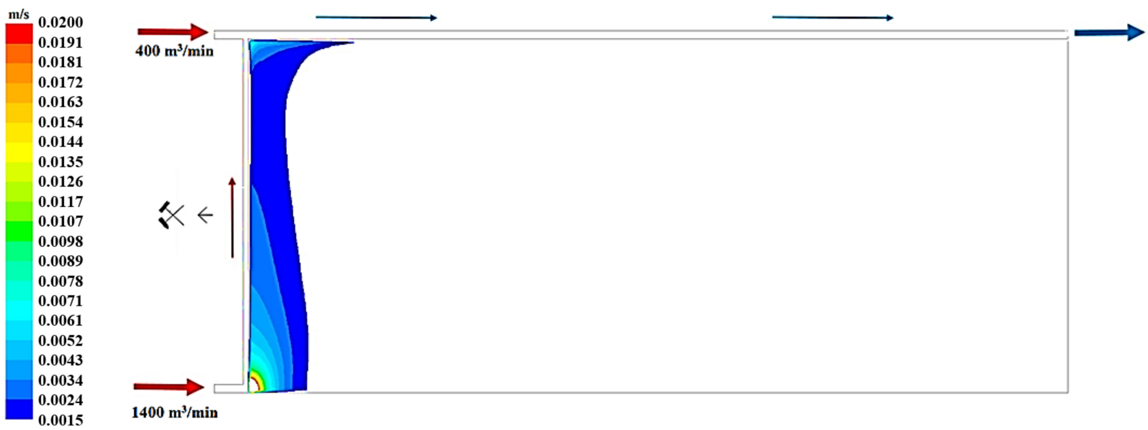


Figure 5. The distribution of the air speed within the range from 0.02 m/s to 0.0015 m/s flowing through the goaves with caving at a distance of 0.5 m from the floor of the exploited seam.

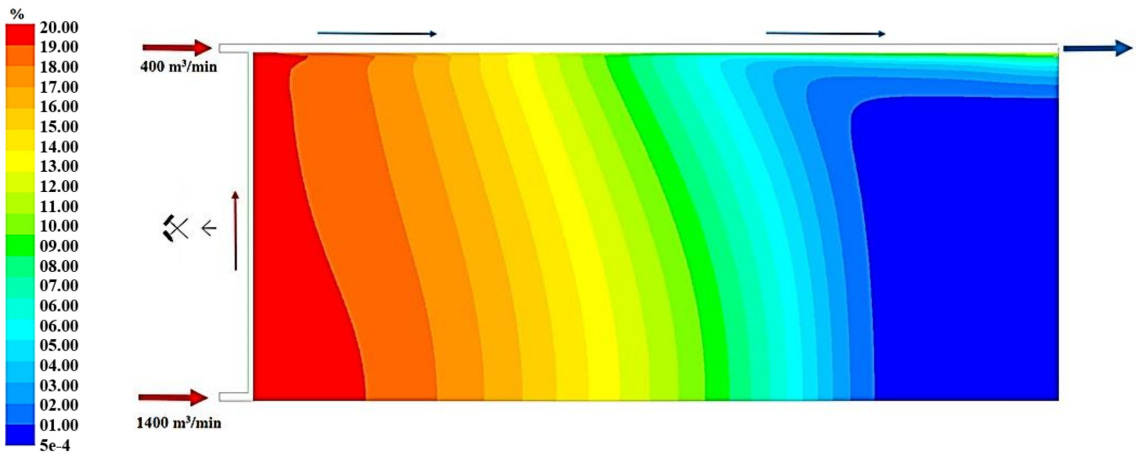


Figure 6. The distribution of oxygen concentration in the air flowing through the goaves with caving at a distance of 0.5 m from the floor of the exploited seam.

Figures 7–9 present, respectively, the distributions of the air speed and the dangerous speed due to the risk of endogenous fires, as well as the oxygen concentration levels in the goaves with caving at a distance of 2.0 m from the floor of the exploited seam.

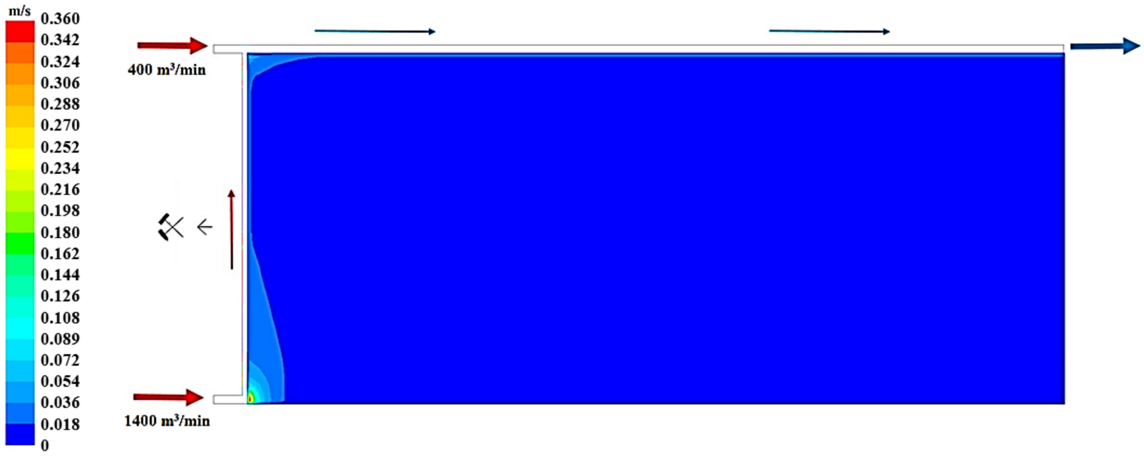


Figure 7. The distribution of the air speed flowing through the goaves with caving at a distance of 2.0 m from the floor of the exploited seam.

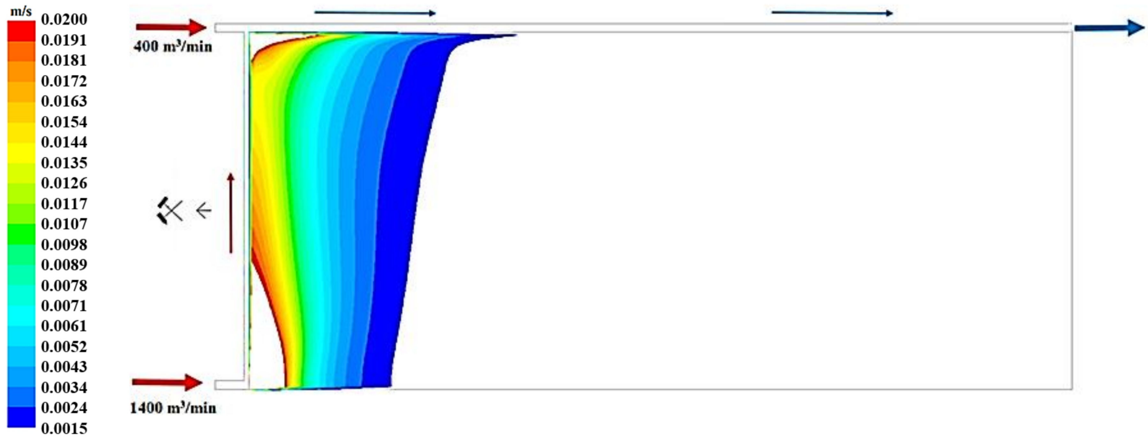


Figure 8. The distribution of the air speed within the range from 0.02 m/s to 0.0015 m/s flowing through the goaves with caving at a distance of 2.0 m from the floor of the exploited seam.

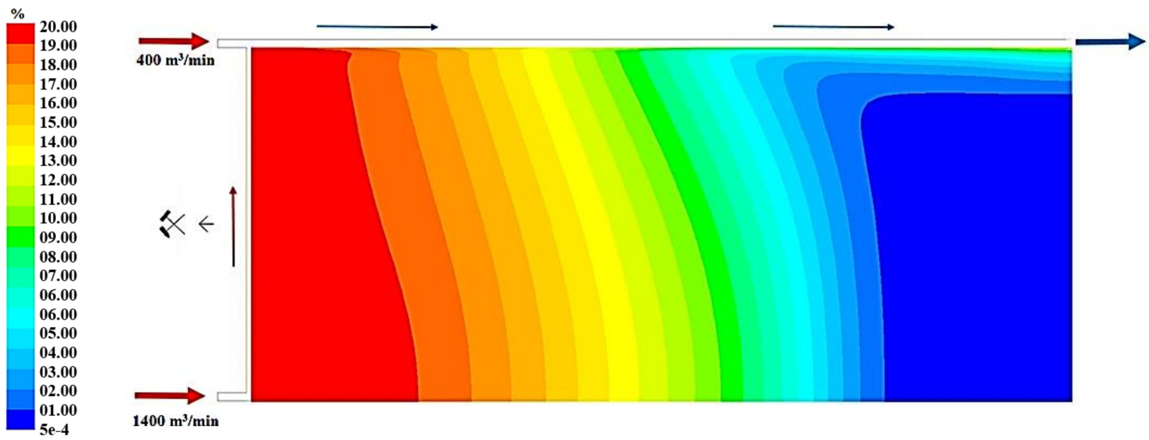


Figure 9. The distribution of oxygen concentration in the air flowing through the goaves with caving at a distance of 2.0 m from the floor of the exploited seam.

Figures 10–12 present, respectively, the distributions of the air speed and the dangerous speed due to the risk of endogenous fires, as well as the oxygen concentration levels in the goaves with caving at a distance of 7.0 m from the floor of the exploited seam.

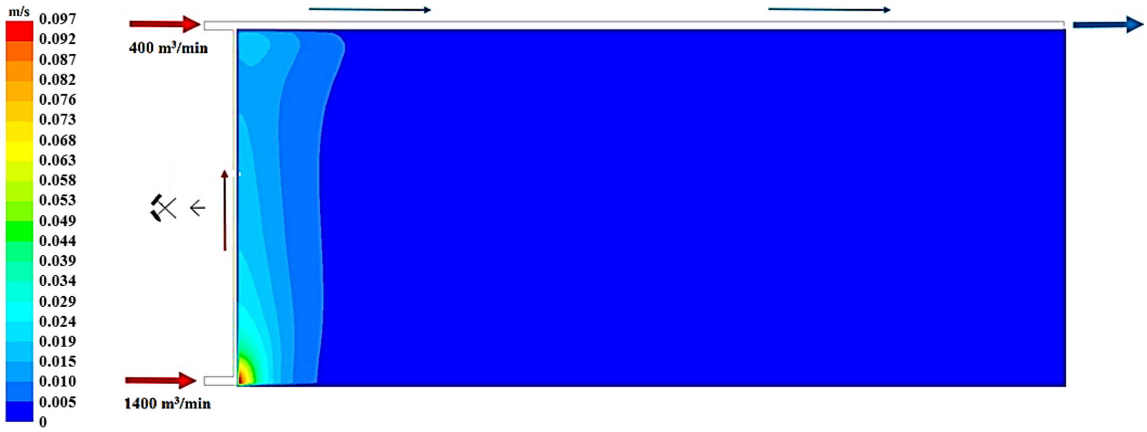


Figure 10. The distribution of the air speed flowing through the goaves with caving at a distance of 7.0 m from the floor of the exploited seam.

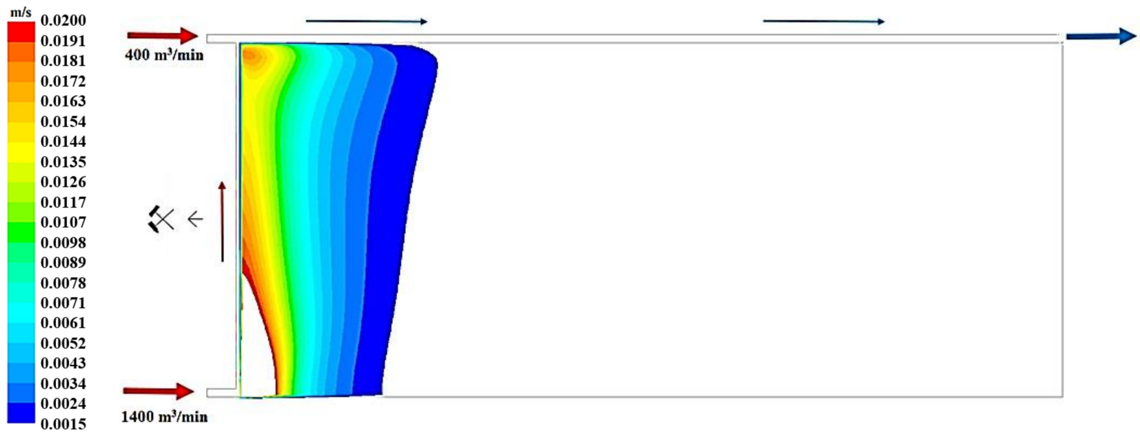


Figure 11. The distribution of the air speed within the range from 0.02 m/s to 0.0015 m/s flowing through the goaves with caving at a distance of 7.0 m from the floor of the exploited seam.

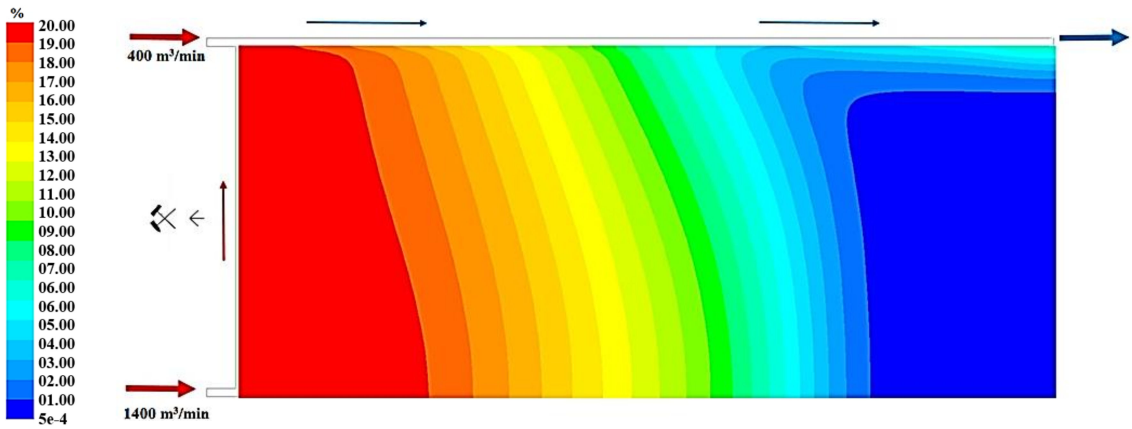


Figure 12. The distribution of oxygen concentration in the air flowing through the goaves with caving at a distance of 7.0 m from the floor of the exploited seam.

Figures 13–15 present, respectively, the distributions of the air speed and the dangerous speed due to the risk of endogenous fires, as well as the oxygen concentration levels in the goaves with caving at a distance of 10.5 m from the floor of the exploited seam.

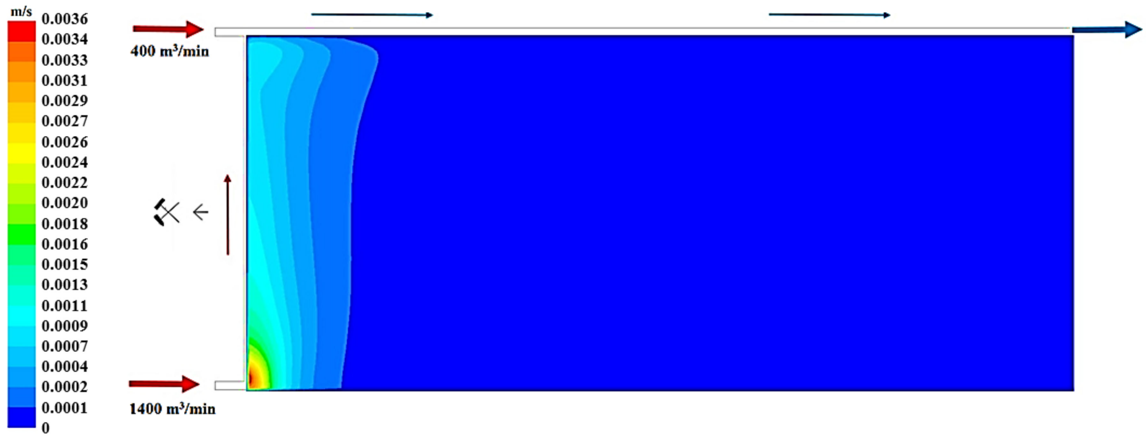


Figure 13. The distribution of the air speed flowing through the goaves with caving at a distance of 10.5 m from the floor of the exploited seam.

Figure 14. The distribution of the air speed within the range from 0.02 m/s to 0.0015 m/s flowing through the goaves with caving at a distance of 10.5 m from the floor of the exploited seam.

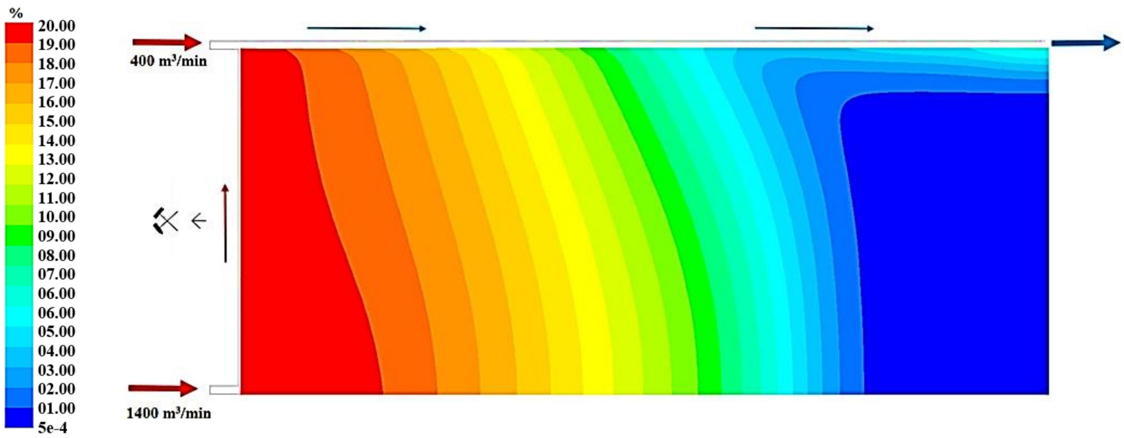


Figure 15. The distribution of oxygen concentration in the air flowing through the goaves with caving at a distance of 10.5 m from the floor of the exploited seam.

Based the results obtained, it may be concluded that the air speed value decreases along with an increase in the distance from the floor of the exploited seam. The air flowing through the goaves with caving reaches the highest speed value, irrespective of the flow height in the goaves, behind the caving line from the inlet side to the longwall, as well as along the tailgate maintained at the goaves. The highest speed value occurs at the flow height of 2.0 m from the floor of the exploited seam in the bottom corner of the longwall, and amounts to 0.36 m/s. The distribution of oxygen concentration for this ventilation system is also different than in the case of the U-type system [47]. It is clearly visible that the air stream moving along with tailgate leads to an increase in this concentration along this route.

Figure 16 presents the distribution of air speed values in the goaves with caving as a function of distance from the longwall front for the actual values of the tensile strength of roof rocks amounting to 3.06 MPa. Red horizontal lines were used to mark the range of dangerous speed values due to the risk of endogenous fires in these goaves.

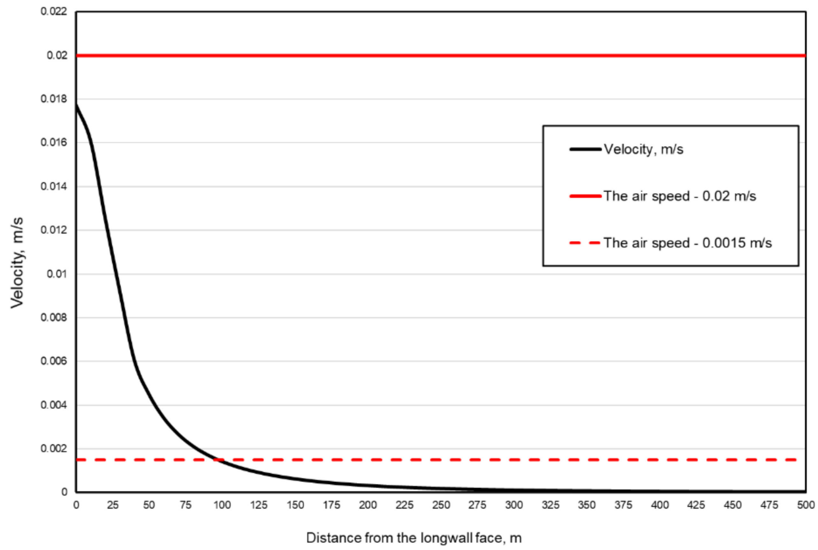


Figure 16. The distribution of air speed values in the goaves with caving as a function of distance from the longwall front for the actual values of the tensile strength of roof rocks amounting to 3.06 MPa.

Based on the determined speed characteristics, it can be concluded that the air speed in goaves with caving decreases along with the increasing distance from the longwall front.

At a distance of up to 96.0 m from the caving line into the depths of the goaves, the speed of the flowing air reaches the critical value due to the risk of endogenous fires, i.e., the value from 0.0015 m/s to 0.02 m/s. After exceeding the distance of 96.0 m from the longwall front, the speed of the air flowing through goaves with caving reaches a value lower than 0.0015 m/s.

Figure 17 presents the distribution of oxygen concentration in the air flowing through the goaves with caving as a function of distance from the longwall front.

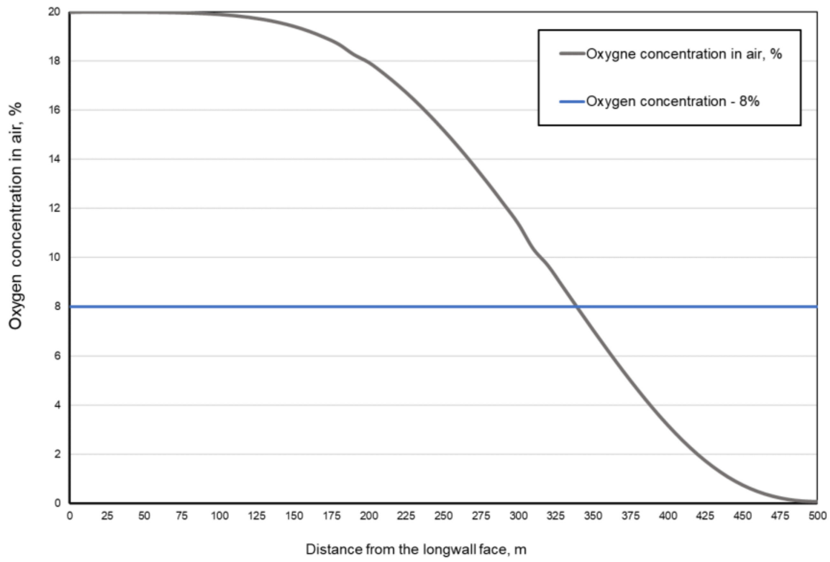


Figure 17. The distribution of oxygen concentration in the goaves with caving as a function of distance from the longwall front for the actual values of the tensile strength of roof rocks amounting to 3.06 MPa.

Based on the determined speed characteristics, it can be concluded that the concentration of oxygen in goaves with caving decreases along with the increasing distance from the longwall front.

At a distance of up to 335.0 m from the caving line inside the goaves, the oxygen concentration in the air flowing through the goaves with caving falls within the critical range due to the risk of endogenous fires, i.e., reaches a value higher than or equal to 8%.

The speed characteristics determined for the air flowing through the goaves with caving and for the oxygen concentration in this air served as the basis for demarcating the zone with a particularly high risk of spontaneous coal combustion (in which both of these conditions are met) (Figure 18).

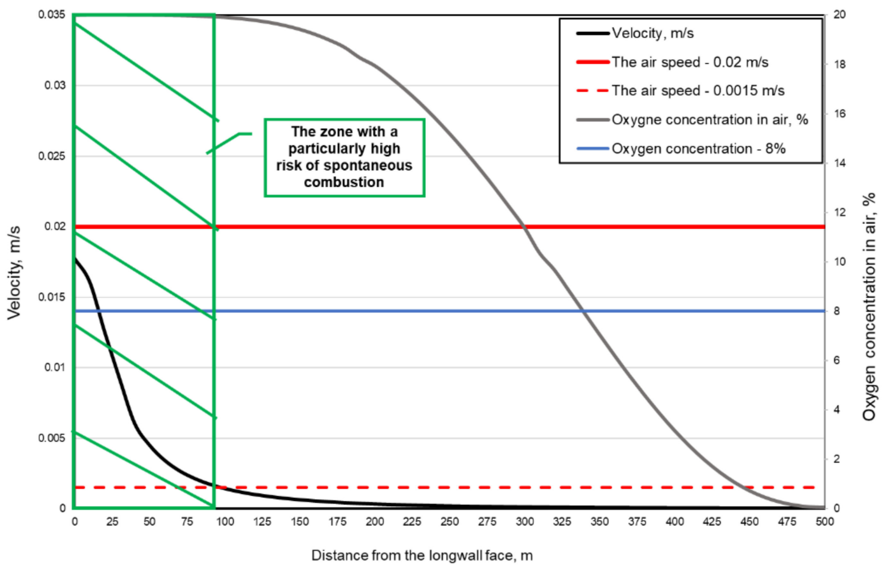


Figure 18. The zone with a particularly high risk of endogenous fires in the goaves formed by rocks with tensile strength equal to 3.06 MPa.

Based on the tests and the results obtained, it was concluded that the zone with a particularly high risk of spontaneous combustion, for the longwall ventilated with the Y-type system, is formed immediately behind the longwall front, and reaches 100.0 m inside the goaves.

Therefore, it can be assumed that the goaves with caving formed by roof rocks whose tensile strength amounts to 3.06 MPa have no cooling zone in which the air (behind the powered roof support along the entire length of the longwall) reaches a flow value higher than 0.02 m/s. This value was exceeded only in the upper and bottom corner of the longwall at the flow height of up to 8.0 m from the floor of the exploited seam.

Behind the zone with a particularly high risk of spontaneous combustion, at a distance of more than 100.0 m from the longwall front to approximately 345.0 m, there forms a zone with insufficient air speed, yet with sufficient oxygen concentration in the air, in terms of the risk of spontaneous coal combustion.

In order to determine the impact of the strength of the rocks forming the caving on the extent of the zone with a particularly high risk of spontaneous combustion for longwalls ventilated with the Y-type system with the air being discharged along the goaves and supplied along the tailgate, additional tests were conducted for different values of this strength (2, 4, 5, 6 and 7 MPa).

Figures 19–30 present the results of the analysis for the goaves with caving formed by roof rocks whose tensile strength is equal to 3.06 MPa (as is the case in a real-world system).

Figures 19–21 present, respectively, the distributions of the air speed and the dangerous speed due to the risk of endogenous fires, as well as the oxygen concentration levels in the goaves with caving at a distance of 0.5 m from the floor of the exploited seam.

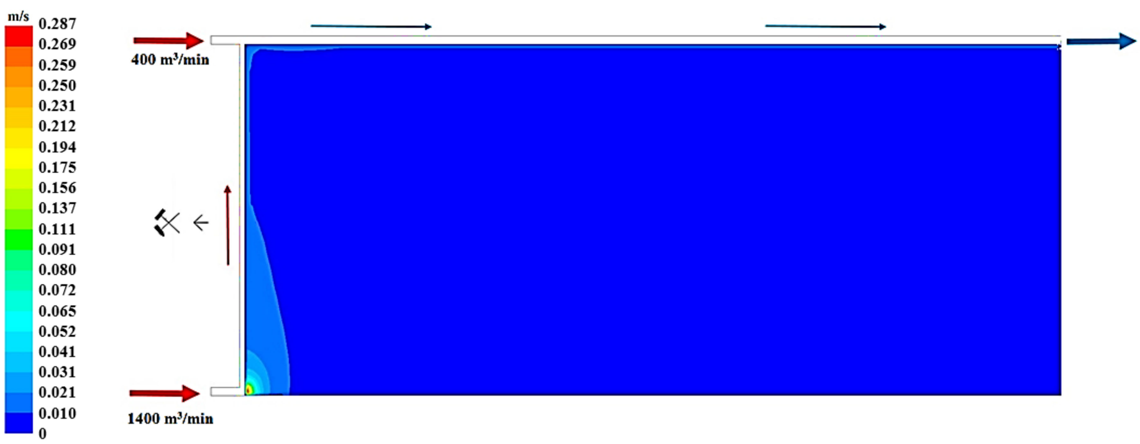


Figure 19. The distribution of the air speed flowing through the goaves with caving at a distance of 0.5 m from the floor of the exploited seam.

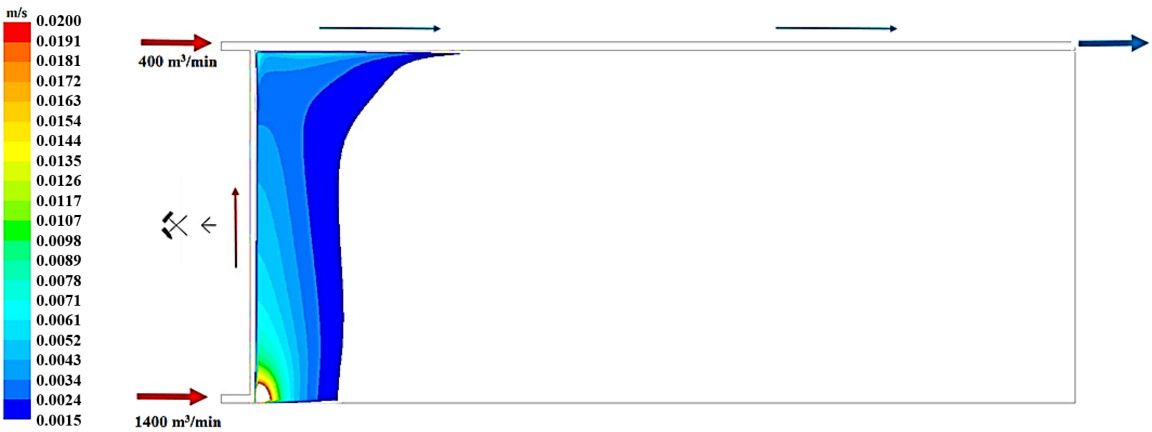


Figure 20. The distribution of the air speed within the range from 0.02 m/s to 0.0015 m/s flowing through the goaves with caving at a distance of 0.5 m from the floor of the exploited seam.

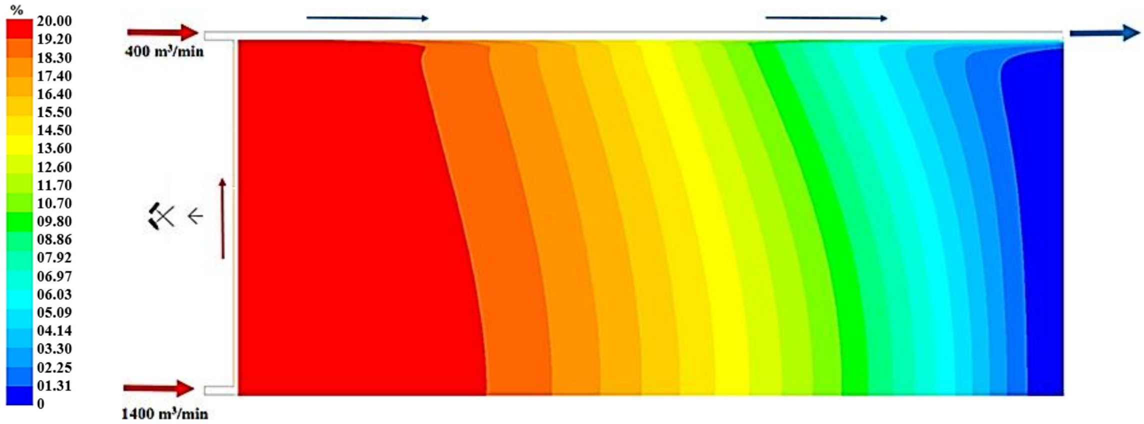


Figure 21. The distribution of oxygen concentration in the air flowing through the goaves with caving at a distance of 0.5 m from the floor of the exploited seam.

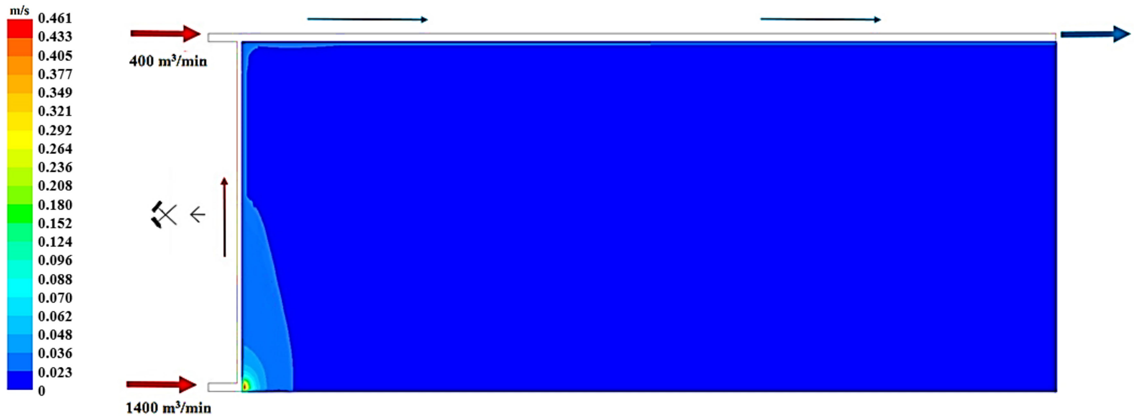


Figure 22. The distribution of the air speed flowing through the goaves with caving at a distance of 2.0 m from the floor of the exploited seam.

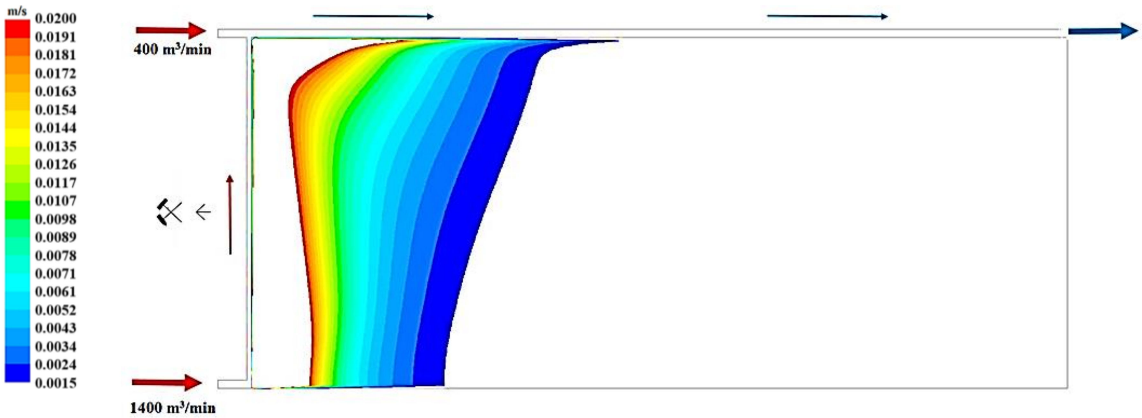


Figure 23. The distribution of the air speed within the range from 0.02 m/s to 0.0015 m/s flowing through the goaves with caving at a distance of 2.0 m from the floor of the exploited seam.

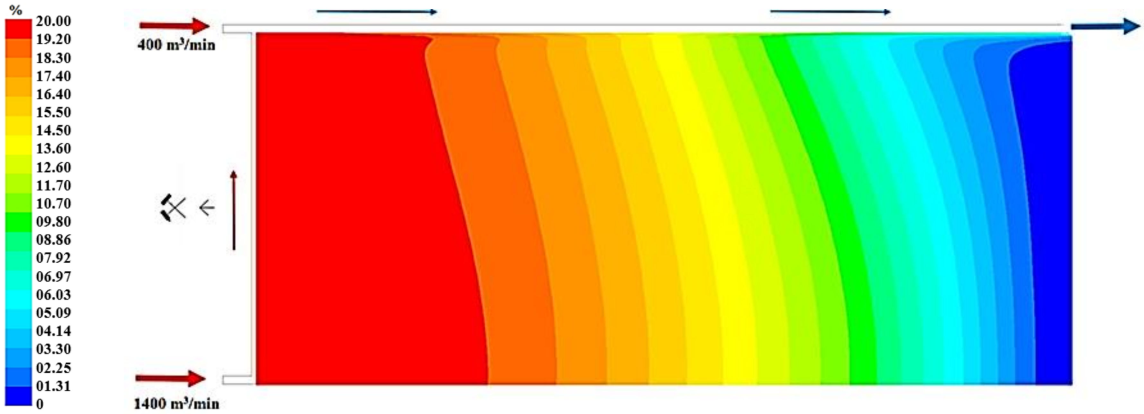


Figure 24. The distribution of oxygen concentration in the air flowing through the goaves with caving at a distance of 2.0 m from the floor of the exploited seam.

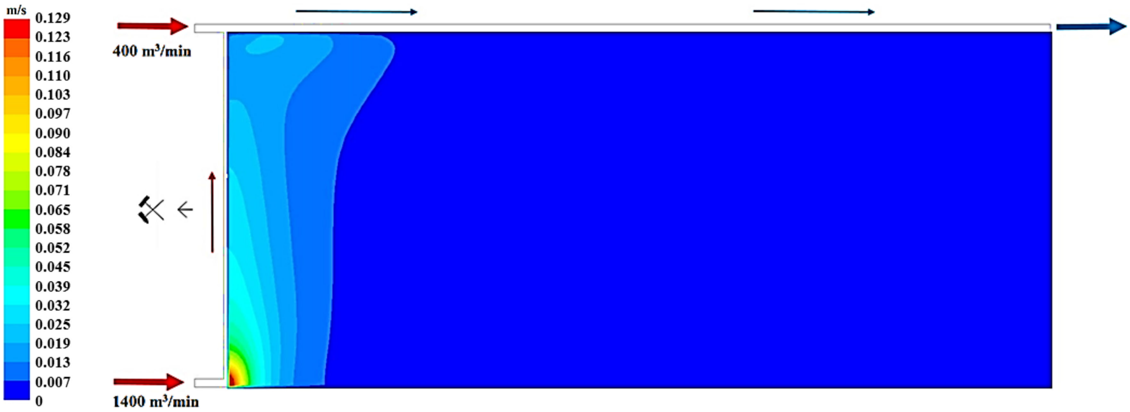


Figure 25. The distribution of the air speed flowing through the goaves with caving at a distance of 7.0 m from the floor of the exploited seam.

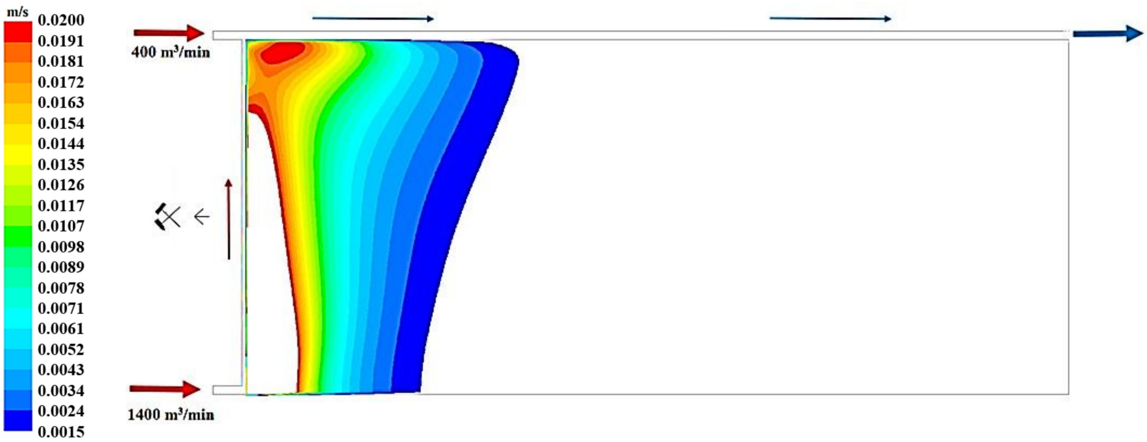


Figure 26. The distribution of the air speed within the range from 0.02 m/s to 0.0015 m/s flowing through the goaves with caving at a distance of 7.0 m from the floor of the exploited seam.

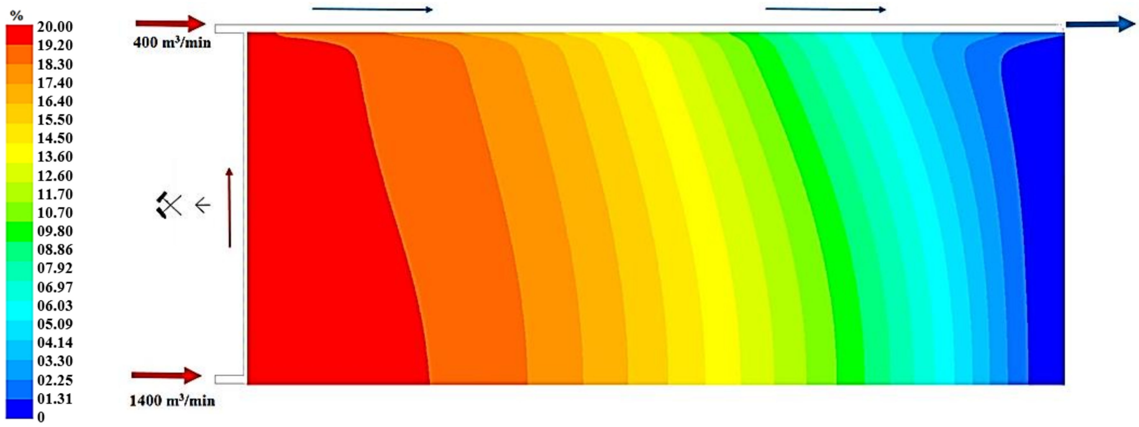


Figure 27. The distribution of oxygen concentration in the air flowing through the goaves with caving at a distance of 7.0 m from the floor of the exploited seam.

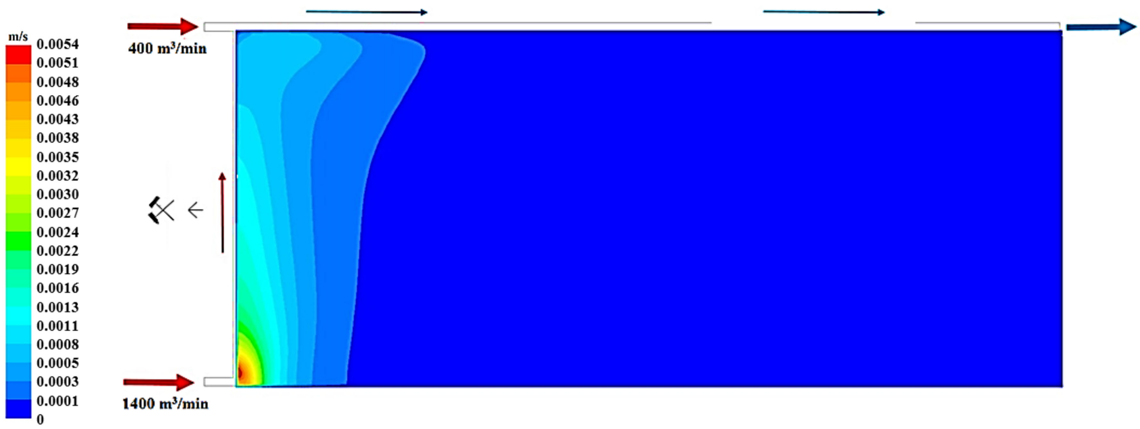


Figure 28. The distribution of the air speed flowing through the goaves with caving at a distance of 10.5 m from the floor of the exploited seam.

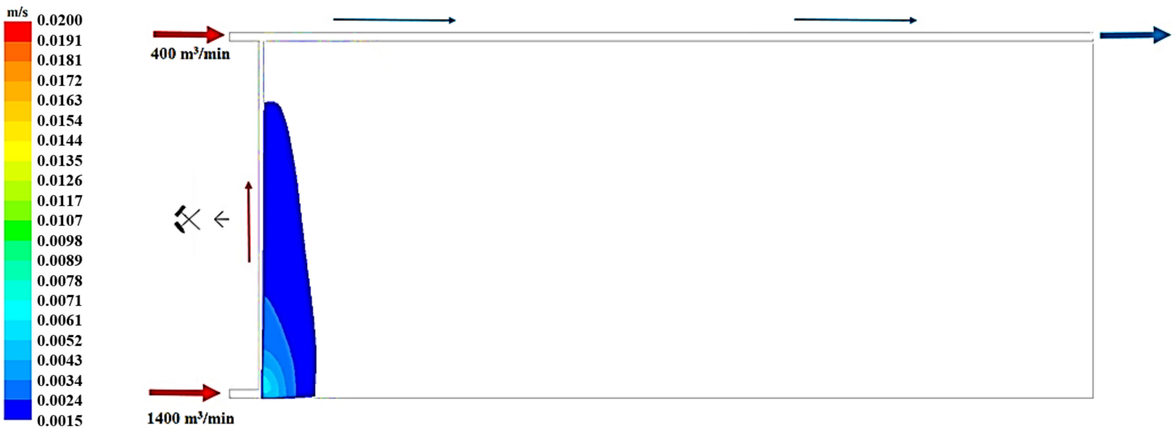


Figure 29. The distribution of the air speed within the range from 0.02 m/s to 0.0015 m/s flowing through the goaves with caving at a distance of 10.5 m from the floor of the exploited seam.

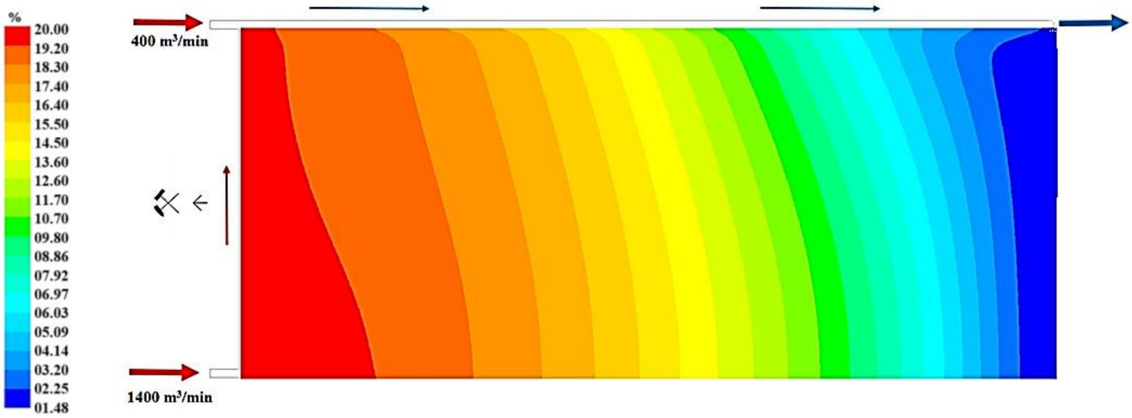


Figure 30. The distribution of oxygen concentration in the air flowing through the goaves with caving at a distance of 10.5 m from the floor of the exploited seam.

Figure 31 presents the distribution of air speed values in the goaves with caving as a function of distance from the longwall front for the actual values of the tensile strength of roof rocks amounting to 6.0 MPa. Red horizontal lines were used to mark the range of dangerous speed values due to the risk of endogenous fires in these goaves.

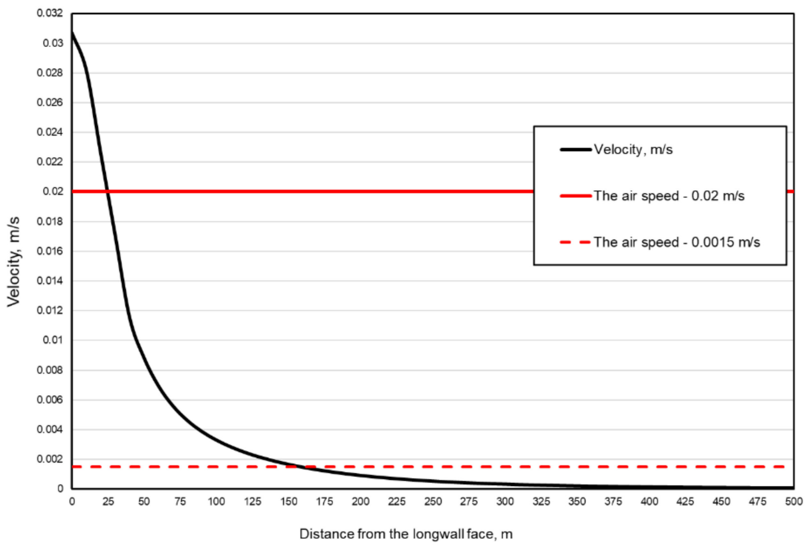


Figure 31. The distribution of air speed values in the goaves with caving as a function of distance from the longwall front for the actual values of the tensile strength of roof rocks amounting to 6.0 MPa.

Based the results obtained, it may be concluded that the air speed value decreases along with an increase in the distance from the floor of the exploited seam.

At a distance of 25.0 m behind the longwall front to 160.0 m inside the goaves, the speed of the flowing air reaches the critical value due to the spontaneous combustion risk, i.e., the value from 0.0015 m/s to 0.02 m/s. After exceeding the distance of 160.0 m from the longwall front, the speed of the air flowing through goaves with caving reaches a value lower than 0.0015 m/s.

Figure 32 presents the distribution of oxygen concentration in the air flowing through the goaves with caving as a function of distance from the longwall front.

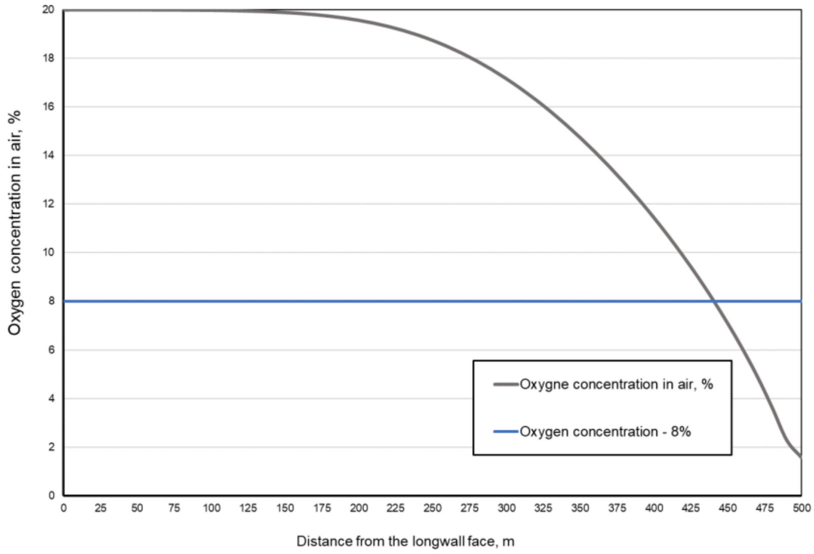


Figure 32. The distribution of oxygen concentration in the goaves with caving as a function of distance from the longwall front for the actual values of the tensile strength of roof rocks amounting to 6.0 MPa.

Based on the determined speed characteristics, it can be concluded that the concentration of oxygen in goaves with caving decreases along with the increasing distance from the longwall front.

At a distance of up to 440.0 m from the caving line inside the goaves, the oxygen concentration in the air flowing through the goaves with caving falls within the critical range due to the risk of endogenous fires, i.e., reaches a value higher than or equal to 8%.

The speed characteristics determined for the air flowing through the goaves with caving and for the oxygen concentration in this air served as the basis for demarcating the zone with a particularly high risk of spontaneous coal combustion (in which both of these conditions are met) (Figure 33).

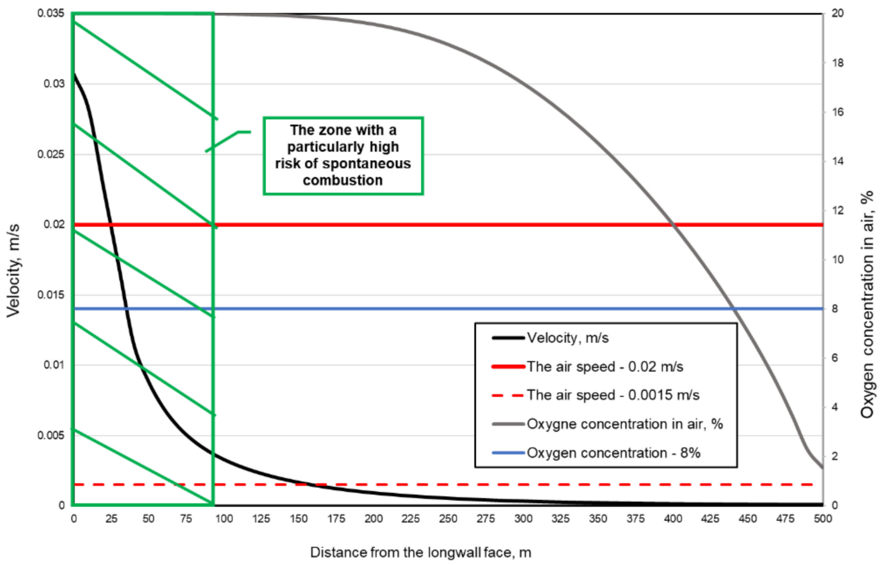


Figure 33. The zone with a particularly high risk of endogenous fires in the goaves formed by rocks with tensile strength equal to 6.0 MPa.

Based on the tests and the results obtained, it was concluded that the zone with a particularly high risk of spontaneous combustion is formed immediately behind the longwall front, and reaches 160.0 m inside the goaves.

In the goaves with caving formed by roof rocks whose tensile strength amounts to 6.0 MPa, the cooling zone in which this air (behind the powered roof support along the entire length of the longwall) reaches a flow value higher than 0.02 m/s occurs at a distance of up to 25.0 m from the longwall front.

Behind the zone of a particularly high risk of spontaneous combustion, at a distance of over 160.0 m from the longwall front to approximately 460.0 m, there forms a zone with insufficient air speed, yet with sufficient oxygen concentration in the air (due to the risk of spontaneous combustion).

The tests conducted made it possible to demarcate the zone with a particularly high risk of spontaneous combustion in the goaves with caving formed by rocks whose tensile strength was equal to 2, 3.06, 4, 5, 6 and 7 MPa. Table 2 summarises the extents of these zones for the actual conditions of the longwall in question as well as for the additional ones obtained from the analyses conducted.

Table 2. The zone with a particularly high risk of spontaneous combustion in the goaves with caving formed by rocks whose tensile strength was equal to 2, 3.06, 4, 5, 6 and 7 MPa.

Tensile Strength of Roof Rock, R_{rrs}, MPa	Critical Air Velocity Zone, m	Critical Oxygen Concentration Zone, m	The Zone with a Particularly High Risk of Spontaneous Combustion, m
2.00	0–70.0 m	0–260.0 m	0–70.0 m
3.06	0–96.0 m	0–335.0 m	0–96.0 m
4.00	8.0–115.0 m	0–370.0 m	8.0–115.0 m
5.00	18.0–138.0 m	0–427.0 m	18.0–138.0 m
6.00	28.0–160.0 m	0–440.0 m	28.0–160.0 m
7.00	37.0–184.0 m	0–460.0 m	37.0–184.0 m

The results obtained unambiguously indicate that the type of roof rocks (defined by their tensile strength) has a significant impact on the value of the air speed flowing through the goaves with caving, and on the value of oxygen concentration in this air. The more resistant the rocks, the greater the extent of the zones in which the air speed and oxygen concentration reach critical values due to the risk of spontaneous coal combustion.

The greater extent of the zone with a particularly high risk of endogenous fires in the caving goaves of the longwall ventilated with the Y-type system (compared, for example, to the U-type system) arises out of the necessity to maintain a tailgate along the goaves, through which the air can flow. Part of the ventilation air stream flowing through this tailgate migrates to the goaves through the sidewalls, thereby increasing the extent of this zone in the goaves.

4. Conclusions

Spontaneous combustion of coal is a highly dangerous phenomenon that occurs during mining exploitation. It leads to major economic losses for mining enterprises and poses a threat to the working crew. The products of coal combustion are also highly damaging to the natural environment. This is because they penetrate into the mining atmosphere along with the ventilation stream, and then to the surface into the natural environment through the ventilation system. As a result, it is necessary to undertake various steps to reduce the risk of these phenomena in mines.

The method developed and presented in the paper for determining the zone with a particularly high risk of spontaneous coal combustion, in this case for longwalls ventilated with the Y-type system, serves this purpose. The determination of such a zone may serve as the basis for taking effective preventive measures. They involve choosing the exploitation speed, isolating this zone, introducing inert gases, sealing the goaves, etc. For these measures to be effective, it is necessary to identify the sites (areas) where spontaneous coal combustion may occur.

It must also be stressed that mining exploitation also generates other hazards that determine, for example, the application of different ventilation systems. Generally speaking, the Y-type ventilation system under analysis is highly favourable in the case of methane threats, and slightly less favourable for the threat related to spontaneous coal combustion. Therefore, the tests conducted are of a particular significance in the process of limiting this threat.

The method developed, thanks to the application of advanced spatial models and the use of actual measurement data from the analysed region, allows for early identification of areas in which spontaneous coal combustion may occur.

The results obtained clearly indicate that the demarcated risk zones of spontaneous coal combustion are significantly higher for this ventilation system than for the U-type system.

The comprehensive analysis also indicates that the type of roof rocks forming the caving has a significant impact on the size and location of the zone with a particularly high risk of spontaneous coal combustion. The different tensile strength of these rocks leads to changes in the porosity and permeability of the caving, which in turn has a significant impact on the ventilation parameters of the air flowing through the caving. No such tests have been conducted so far, and the results obtained indicate the significant changes in the location and extent of the risk zone along with the changing values of this strength.

The results obtained also enhance knowledge about the ventilation of underground exploitation regions and should become an important source of information for the ventilation service teams in mines. In particular this concerns the essential differences in this process for the U-type and Y-type ventilation systems, as unequivocally indicated by the results obtained.

These results also demonstrate the great impact exerted on the ventilation process in mine headings by the goaves with caving, which—due to their porosity—must be taken into consideration in this process.

The methodology developed and presented in the paper is of a universal nature and may be successfully applied to multivariate analyses of the spontaneous combustion hazard, as well as on the mining landfill sites.

The authors hope that the results obtained and the methodology developed will find broader application for the support of preventive measures in terms of limiting the risk of spontaneous coal combustion.

Author Contributions: Conceptualization, M.T. and J.B.; methodology, J.B. and M.T.; software, M.T.; validation, J.B. and M.T.; formal analysis, J.B. and M.T.; investigation, J.B. and M.T.; resources, J.B. and M.T.; data curation, J.B. and M.T.; writing of the original draft preparation, J.B. and M.T.; writing of review and editing, J.B. and M.T.; visualization, M.T.; supervision, J.B.; project administration, J.B.; funding acquisition, M.T. and J.B.

Funding: This research was funded by SUBB, grant numbers 06/030/BKM_18/0041, 06/030/BKM_19/0048.

Conflicts of Interest: The authors declare no conflict of interest.

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