

# Influence of the Volumetric Expenditure of Air Supplied to the Longwall Through the “Y” Ventilation System on the Location of an Area at the Risk of an Endogenic Fire

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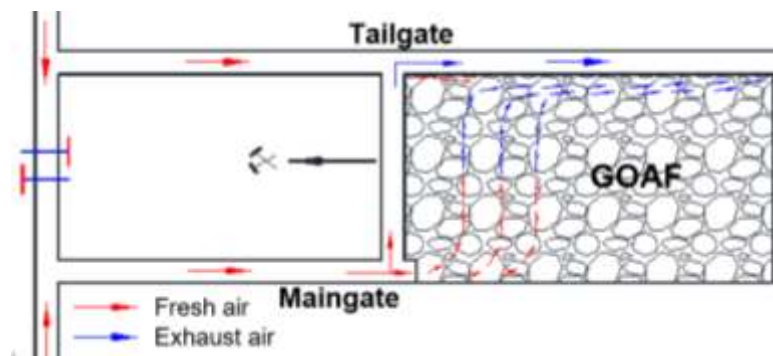
## INTRODUCTION

Many hazards in underground hard coal mines are reported, including natural hazards, which significantly affect work safety and the efficiency of the production process (Brodny and Tutak, 2016a; Szurgacz et al., 2019; Tutak and Brodny, 2017a). One of the commonly occurring natural hazards is the threat of underground endogenous fires, which may occur in mining excavations or their immediate surroundings, e.g. in goaves. These fires arise from the oxidation of coal, leading to its self-ignition (Brodny and Tutak, 2018; Brodny and Tutak, 2016b; Li et al., 2008; Tutak and Brodny, 2017b; Tutak and Brodny, 2018; Wang et al., 2015; Yuan and Smith, 2008; Yuan and Smith, 2009).

In total, 63 endogenous fires were reported in Polish hard coal mines between 2009-2018, of which 29 were located in the area of longwalls. The most common place where endogenous fires occur in the area of longwalls are goaves (WUG, 2009-2018).

A goaf zone is a space created after the mined coal. It is filled with rock rubble formed as a result of the collapse of roof rocks lying above the exploited deposits. From the point of view of the threat of endogenous fires, very important properties of this center are porosity and permeability. These features make it possible for gas to flow through a goaf, including air, which migrates as a result of longwall ventilation.

The air entering goaves, usually with high oxygen content, is one of the necessary conditions for an endogenous fire to start. For this reason, the way of ventilating longwall galleries during mining operations is of great significance. This ventilation can take place using a variety of systems, but the most commonly used in Polish mine conditions are the U and Y systems (Tutak and Brodny, 2019). A crucial factor that affects the selection of the optimal wall ventilation system is the intensity of the ventilation hazards in the area of exploitation. These threats include both endogenous fires and methane hazards. In the case of the expected high methane hazard, the Y ventilation system is oftentimes chosen at the planning stage of operations (Fig. 1).



**Fig. 1 The Y ventilation system**

Source: (Own elaboration based on Tutak and Brodny, 2019)

From the point of view of endogenous fire hazards, this phenomenon is very unfavorable. It causes an intense air supply to goaf zones, and thus favorable conditions for self-heating of coal left there. The coal left in goaves is the result of either its incomplete exploitation or the occurrence of carbon bottom or roof battens.

One of the factors that is essential for the intensity of air flow through goaves is the amount of air supplied to the longwall. This amount depends, among others, on the size of the methane hazard – the larger it is, the more air is needed to maintain a safe mine atmosphere composition. However, this causes an increased air flow through a goaf zone and thus a greater possibility of an endogenous fire. An endogenous fire can occur in goaf zones only with the presence of shredded coal prone to self-ignition and the air flow velocity through goaves from 0.0015 m/s to 0.02 m/s (Tutak and Brodny, 2019). At the same time, the oxygen concentration level in this air must be not less than 8%. The distribution of air velocity in goaves and oxygen concentration is influenced by many factors, for example, the type of roof rocks, methane content and the amount of air supplied to the longwall. This value determines both the amount and speed of air moving in goaves, i.e. the size of the zone in which the conditions necessary for an endogenous fire to start are met.

So far, no research has been carried out to determine the impact of the volumetric expenditure of air supplied to the longwall ventilated with the Y system on the location of an area at the risk of an endogenous fire. Practice shows, however, that the amount of this expenditure, measured by the speed of air flow, with constant goaf dimensions, has a significant impact on the location and size of this area.

Nevertheless, under real conditions, it is impossible to designate such an area. Therefore, it is necessary to use other alternative methods. Model studies based on numerical analyses create such possibilities. This type of studies use the structural model of the studied area and make it possible to determine an area in which an endogenous fire may occur in goaves, depending on the volume of air supplied to the longwall. Knowledge of the location of this area help to take appropriate preventive measures to limit the possibility of the emergence and development of the coal self-heating process, leading to an endogenous fire.

Model studies were carried out for the actual layout of mining excavations for the longwall ventilated with the Y system. For three values of the volume expenditure of air supplied to the longwall, the location of an area at the risk of an endogenous fire was designated.

## METHODOLOGY OF RESEARCH

The aim of the study was to determine the impact of the volumetric expenditure of air supplied to the longwall ventilated with the Y system on the location of an area in goaf zones at the risk of an endogenous fire. The studies were carried out for a spatial model reflecting the real longwall together with longwall galleries and goaf zones.

The numerical fluid mechanics and the finite volume method were utilized, as well as the Ansys Fluent program based on this method.

### Mathematical models of flow

The flow of the air stream mixture is described by constitutive equations, which comprise mass, momentum and energy conservation equations, as well as the species transport equation (Brodny et al., 2018; Brodny and Tutak, 2019; Kurnia et al. 2014; Kurnia et al., 2016):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot \rho \mathbf{v} \mathbf{v} = -\nabla p \cdot \nabla \boldsymbol{\tau} + \rho \mathbf{g} \quad (2)$$

$$\frac{\partial}{\partial t} (\rho c_p T) + \nabla \cdot (\rho c_p \mathbf{v} T) = \nabla \cdot \left( k_{eff} + \frac{c_p \mu_t}{Pr_t} \right) \nabla T \quad (3)$$

$$\frac{\partial}{\partial t} (\rho \omega_i) + \nabla \cdot (\rho \omega_i \mathbf{U}) = \nabla \cdot \left( \rho D_{i,eff} + \frac{\mu_t}{Sc_t} \right) \nabla \omega_i \quad (4)$$

where:

$\rho$  is the gas density (kg/m<sup>3</sup>),

$\mathbf{U}$  is the gas velocity (m/s),

$p$  is pressure (Pa),

$\boldsymbol{\tau}$  is the viscous stress tensor (Pa),

$\mathbf{g}$  is gravity acceleration (m·s<sup>-2</sup>),  $c_p$  is the specific heat of the gas,

$k_{eff}$  is the effective gas thermal conductivity,

$T$  is the temperature (K),

$\omega_i$  is the mass fraction of species  $i$  (N<sub>2</sub>, O<sub>2</sub> and CH<sub>4</sub>),

$\mu_t$  is turbulent viscosity (Pa·s),

$D_{i,eff}$  is the effective diffusivity of species  $i$  (m<sup>2</sup>/s),

$Sc_t$  is the turbulent Schmidt number (0.7),

$Pr_t$  is the turbulent Prandtl number.

The stream of air and methane mixture flowing through the longwall and longwall galleries, as well as the initial section of goaf zones is turbulent. Therefore, in order to mathematically map a turbulent flow, it is necessary to include in the model, which describes this flow, additional equations describing this type of flow.

In the turbulence model  $k$ - $\varepsilon$ , in the standard variation, the basic Navier-Stokes equation was 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. In order 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 (Ansys, 2011; Brodny et al., 2018; Brodny and Tutak, 2019):

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

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

where:

$C_{1\varepsilon}$ ,  $C_{2\varepsilon}$ ,  $C_{3\varepsilon}$  are constants,

$\sigma_k$ ,  $\sigma_\varepsilon$  are turbulent Prandtl numbers for  $k$  and  $\varepsilon$ ,

$G_b$  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 the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate,

$S_k$ ,  $S_\varepsilon$  are user-defined source terms.

Since a laminar flow also takes place in goaf zones, it is crucial to consider the source part  $S_i$  in the momentum conservation equation. The additional source part takes the following form (Ansys, 2011):

$$S_i = - \left( \sum_{j=1}^3 K_{ij} \mu u_i + \sum_{j=1}^3 C_{ij} \frac{1}{2} \rho u_i^2 \right) \quad (7)$$

where:

$C_2$  is the inertial resistance factor.

### Permeability and porosity of goafs

The presented analysis regards a goaf zone as both a porous and permeable medium. The permeability coefficient of goaves can be determined from following the equation (for  $0 \leq x \leq 2/3 l$ ) (Szlązak, 2001):

$$k(x) = \frac{\mu_g}{r_0 + ax^2} \text{ m}^2 \quad (8)$$

where:

$\mu_g$  is the coefficient of dynamic viscosity of air ( $\text{Nsm}^{-2}$ ),

$l$  is the total length of the longitudinal longwalls (m),

$r_0$  and  $a$  are empirical coefficient;

and from following the equation (for  $2/3 l \leq x \leq l$ ) (Szlązak, 2001):

$$k(x) = \frac{\mu}{r_0 + a \left( \frac{4}{3} l - x \right)^2} \text{ m}^2 \quad (9)$$

The value of the permeability coefficient of goaves  $k_0$  behind the longwall front is determined from the following relationship (Szlązak, 2001):

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

The porosity of goaf zones varies on the basis of the “O-zone theory” (Dai et al. 2012; Xu et. al., 2010). The porosity distribution along the strike direction in the middle of the working face goaves is determined from the following equation (Xu et. al., 2010):

$$n_x = 0.2e^{-0.0223x} + 0.1 \quad (11)$$

where:

$n_x$  is the porosity distribution along the middle line of working face of the longwall ventilated with Y in a goaf zone (%);  $x$  is the  $x$  position of a goaf (m).

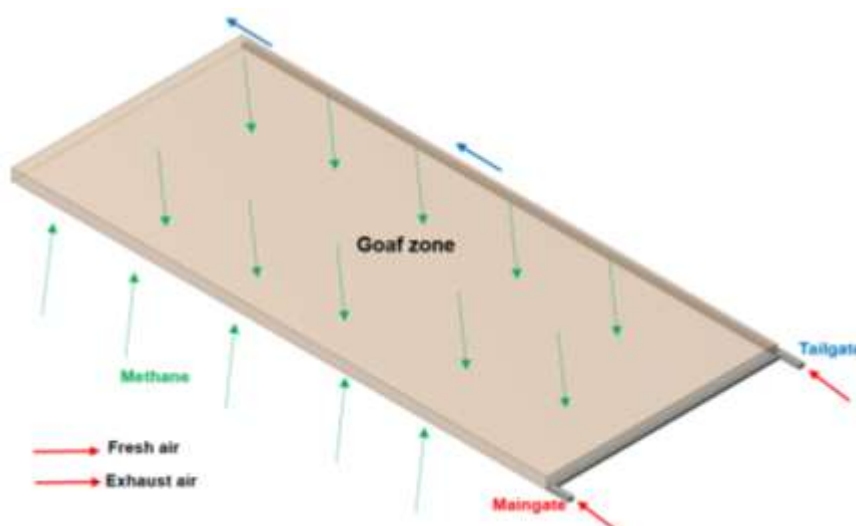
The porosity of a goaf zone in the dip distribution can be determined from the equation:

$$n_y = e^{-0.015y} + 1 \text{ for } 0 < y < \frac{L}{2} \quad (12)$$

### Problem statement and boundary conditions

The basic stage of the research was to develop a numerical model of the real longwall area. This area includes goaves, longwalls and longwall galleries.

The geometric model of the studied longwall ventilated with the Y system is shown in Figure 2, and the basic mining and geological parameters in Table 1.



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

Source: (Own elaboration)

**Table 1 Geometry, Ventilation Parameters and Geological Parameters**

Parameters	Values
Volumetric flow rate of the air supplied to the longwall, m <sup>3</sup> /min	1000/1200/1400
Air supplied through the tailgate, m <sup>3</sup> /min	410
Methane emission rate (absolute methane content), m <sup>3</sup> /min	15
Length of the longwall, m	220
Height of the longwall, m	3
Length of the section of goaves with caving, m	500
Length of the section of the longwall gallery, m	20.0
Cross-sectional area of the longwall gallery, m <sup>2</sup>	15.0
Length of the tailgate maintained along the goaves with caving, m	525
Width of the excavation, m	4.0
Tensile strength of the roof rock, MPa	2.9

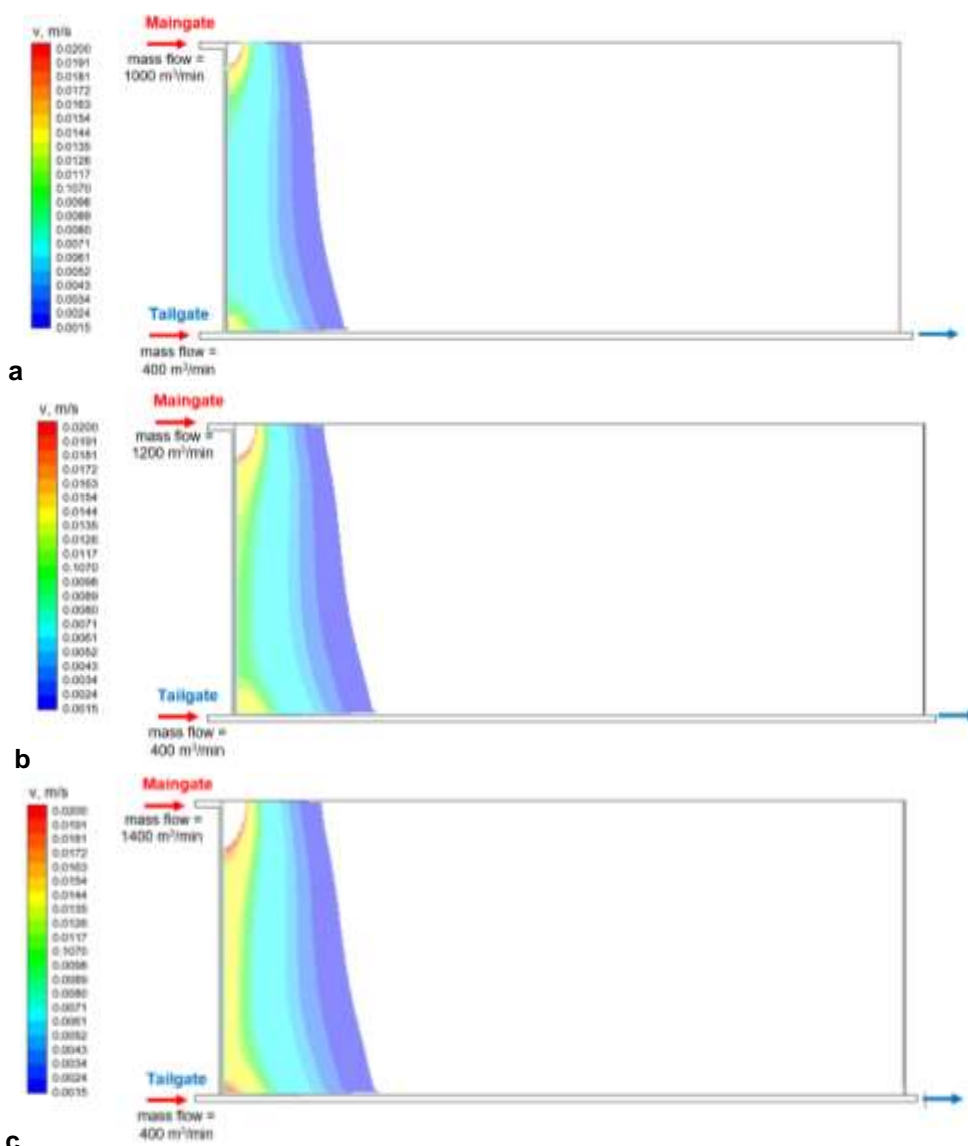
Source: (Own elaboration)

The vertical range of airflow in the goaves was 3.5 x the thickness of the exploited deposit. The tests were performed for three different expenditures of air supplied to the longwall: 1000 m<sup>3</sup>/min, 1200 m<sup>3</sup>/min and 1400 m<sup>3</sup>/min. Such models, along with the adopted conditions of uniqueness, were subjected to numerical analysis.

**RESULTS AND DISCUSSION**

The study allowed for the determination of both physical and chemical parameters of the air and methane mixture flowing through the studied area for various volumetric expenditures of air supplied to the longwall.

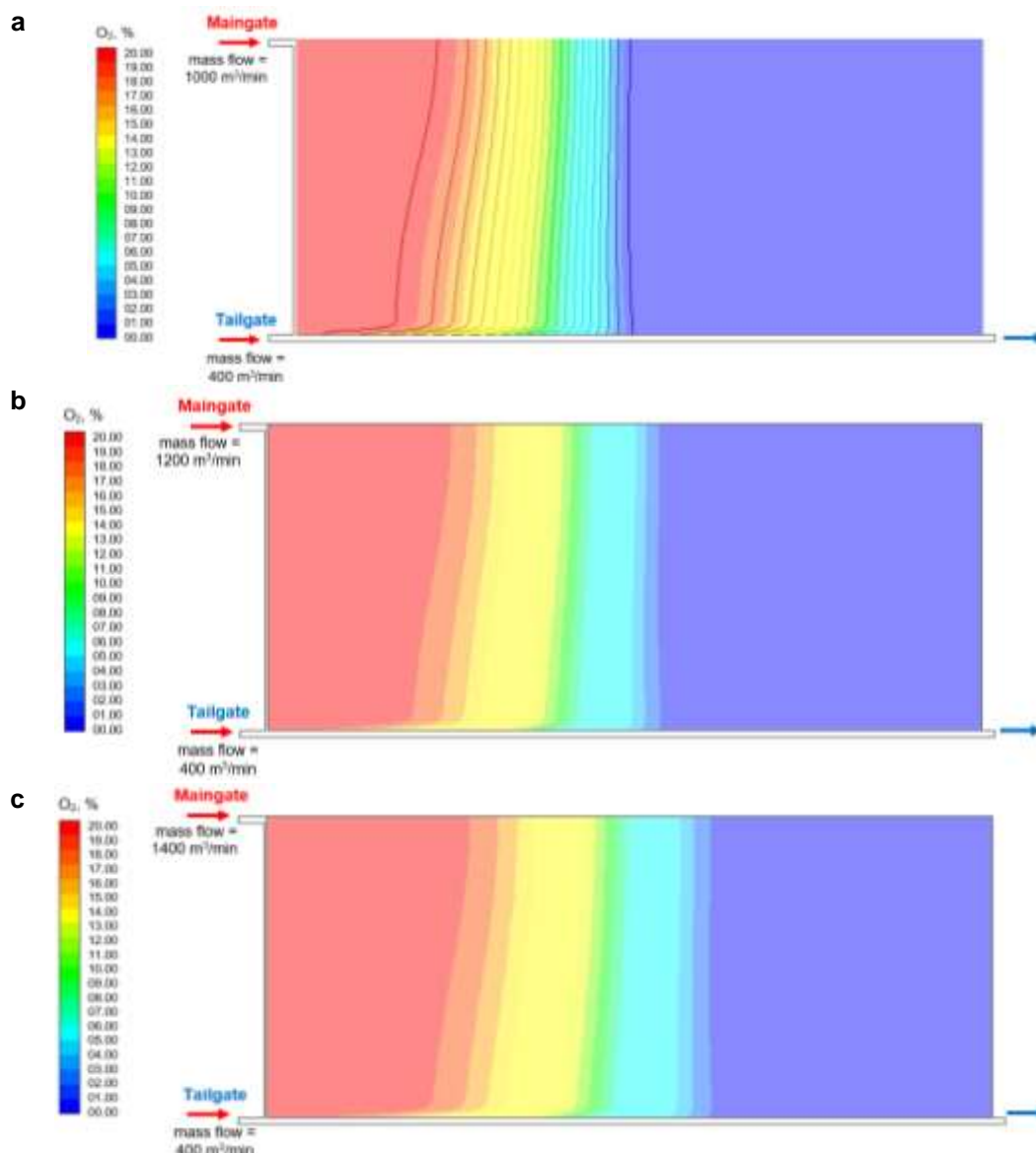
Figure 3 presents air velocity distribution in the goaves, beneficial for the process of heat accumulation and coal self-heating for the studied volumetric expenditures.



**Fig. 3 Distribution of air velocity in the goaves used for the process of heat accumulation and coal self-heating (a - for air expenditure supplied to the longwall 1000 m<sup>3</sup>/min, b - for air expenditure supplied to the longwall 1200 m<sup>3</sup>/min, c - for air expenditure to the longwall 1400 m<sup>3</sup>/min)**

Source: (Own elaboration)

On the other hand, Figure 4 presents oxygen concentration distributions for the goaves.



**Fig. 4** Distribution of oxygen concentration in the goaves (a - for air expenditure supplied to the longwall 1000 m<sup>3</sup>/min, b - for air expenditure supplied to the longwall 1200 m<sup>3</sup>/min, c - for air expenditure supplied to the longwall 1400 m<sup>3</sup>/min)

The conducted studies and determined air velocity distributions in the goaves and oxygen concentration in this air enabled the determination of areas in the goaves at the risk of an endogenous (Table 2).

The results clearly indicate that the volumetric expenditure of air supplied to the longwall ventilated with the Y system has a significant impact on the value of air velocity flowing through the goaf zones and the value of oxygen concentration in this air. The larger it is, the greater the range of the area in the goaves, where the air velocity and oxygen concentration reach dangerous values due to the coal self-heating process, leading to an endogenous fire.

**Table 2 The range of the area at the risk of an endogenous in the goaf zones for various volumetric expenditures of the air stream supplied to the longwall**

The volumetric flow rate of the air supplied to the longwall, m <sup>3</sup> /min	Critical air velocity zone in the goaf, m	Critical oxygen concentration zone in the goaf, m	The zone with a particularly high risk of endogenous fires, m
1000	0-69.0	0-198.0	0-69.0
1200	0-79.0	0-218.0	0-79.0
1400	0-89.0	0-248.0	0-89.0

Source: (Own elaboration)

## CONCLUSION

Endogenous fires are considered immensely dangerous phenomena in the mining process. Their occurrence causes a great threat to the working crew and is associated with huge material losses. Most frequently, such fires are reported in goaf zones. This is due to the fact that these goaves are both porous and permeable, which means that both air and oxygen can move freely within them. The developed methodology and conducted studies clearly show that the volumetric expenditure of air supplied to the longwall has a significant impact on the area where a fire may occur. This is particularly important for the Y ventilation system, in which this area reaches large dimensions (Table 2). This can result in a high probability of such a fire for the longwall being tested. This, in turn, is associated with a threat to the crew (carbon monoxide release) and large economic losses caused by shutting down the longwall. In order to avoid such a situation, it is reasonable to use the results obtained for preventive measures. The designated area is a space where these activities should be concentrated, preventing the ignition of a fire, e.g. by injecting inert gases. The results clearly indicate that the volumetric expenditure of air supplied to the longwall by a bottom road has a significant impact on the range of an area deep in goaves, where an endogenous fire may occur.

The results also broaden the knowledge of the ventilation process of the longwall with the Y system, which is used in the case of a high methane hazard in the longwall. These results also demonstrate that goaves have an impact on the ventilation process of mining excavations, which, due to their porosity and permeability, must be taken into account in this type of analysis.

## REFERENCES

- ANSYS. (2011). Ansys Theory Guide; ANSYS, Inc.: Canonsburg, PA 15317., USA.
- Brodny, J. and Tutak, M. (2019). Forecasting the distribution of methane concentration levels in mine headings by means of model-based tests and in-situ measurements. *Archives of Control Sciences*, 29(1), pp. 25-39.
- Brodny, J. and Tutak, M. (2018). Determination of the zone with a particularly high risk of endogenous fires in the goaves of a longwall with caving. *Journal of Applied Fluid Mechanics*, 11(3), pp. 545-553.
- Brodny, J.; Tutak, M. and John, A. (2018). The impact of airway geometry on the distribution of methane concentrations at the outlet from a longwall. *Mechanika*, 24(5), pp. 695-702.
- Brodny, J. and Tutak, M. (2016a). Analysis of gases emitted into the atmosphere during an endogenous fire. *Proceedings of 16<sup>th</sup> International Multidisciplinary Scientific*



- GeoConference SGEM 2016, pp. 75-82. DOI: 10.5593/SGEM2016/HB43/S06.011.
- Brodny, J. and Tutak, M. (2016b). The impact of the flow volume ventilation to the location of the special hazard spontaneous fire zone in goaf with caving of operating longwalls. Proceedings of the 16<sup>th</sup> International Multidisciplinary Scientific GeoConference. SGEM 2016, pp. 897-904, doi:10.5593/SGEM2016/B12/S03.115.
- Dai, G.; Zhang, S. and Tang, M. (2012) Determination of spontaneous combustion “three zones” in goaf of no. 713 fully mechanized longwall of qinan coal mine. AGH J. Min. Geoengin, 36, 99-113.
- Kurnia, J.C., Sasmito, A.P. and Mujumdar; A.S. (2014). Simulation of a novel intermittent ventilation system for underground mines. Tunnelling and Underground Space Technology, 42, pp. 206-215.
- Kurnia, J.C., Xu, P. and Sasmito, A. (2016). A novel concept of enhanced gas recovery strategy from ventilation air methane in underground coal mines e A computational investigation. Journal of Natural Gas Science and Engineering, 35, pp. 661-672.
- Li, Z.X.; Wu, Q. and Xiao, Y.N. (2008). Numerical simulation of coupling mechanism of coal spontaneous combustion and gas effusion in goaf. J. China Univ. Min. Technol, 37, 38-42.
- Szlązak, J. (2001). The determination of a co-efficient of longwall gob permeability. Arch. Min. Sci., 46, 451-468.
- Szurgacz, D.; Sobik, L. and Brodny, J. (2019). Integrated method of reducing the threat of endogenous fires in hard coal mines. E3S Web of Conferences, 105,01013.
- 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 – Case Study. Appl. Sci. 9, 5315.
- Tutak, M. and Brodny, J.(2018). Impact of type of the roof rocks on location and range of endogenous fires particular hazard zone by in goaf with caving. E3S Web Conferences Volume 29. DOI:10.1051/e3sconf/20182900005.
- Tutak, M. and Brodny, J. (2017a): Analysis of Influence of Goaf Sealing from Tailgate On the Me-thane Concentration at the Outlet from the Longwall. IOP Conf. Series: Earth and Environmental Science 95 042025. doi:10.1088/1755-1315/95/4/042025.
- Tutak, M. and Brodny, J. (2017b): Determination of Particular Endogenous Fires Hazard Zones in Goaf with Caving of Longwall. IOP Conf. Series: Earth and Environmental Science 95 (2017) 042026 DOI:10.1088/1755-1315/95/4/042026.
- Xu, Q.; Yang, S.Q.; Wang, C.; Chu, T.X.; Ma, W.; Huang, J. (2010). Numerical simulation of gas flow law in stope under stereo gas drainage. J. Min. Saf. Eng. 27, pp. 62-66.
- Wyższy Urząd Górniczy, (2003-2018). Niebezpieczne zdarzenia, Available at: <http://www.wug.gov.pl/bhp/zdarzenia> [Accessed 1 May 2020].
- Wang, Y.; Zhang, X.; Sugai, Y. and Sasaki, K. (2015). A Study on Preventing Spontaneous Combustion of Residual Coal in a Coal Mine Goaf. J. Geol. Res., 712349.
- Yuan, L. and Smith, A.C. (2008). Numerical study on effects of coal properties on spontaneous heating in longwall gob areas. Fuel, 87, 3409–3419.
- Yuan, L. and Smith, A.C. (2009). CFD modeling of spontaneous heating in a large-scale coal chamber. J. Loss Prev. Process Ind., 22, pp. 426-433.

**Abstract:** In the case of longwall ventilation, in the underground hard coal mines, a phenomenon related to the migration of a certain amount of the air stream supplied to the longwall deep into goaf zones occurs. One of the wall ventilation systems, in which this phenomenon is quite intense, is the so called "Y" ventilation system. This migration is immensely unfavorable because it can lead to the self-heating process of coal left in a goaf and, consequently, to an endogenous fire. Such a fire is a great threat to both the safety and continuity of operation processes. For this reason, various activities are undertaken to prevent such a fire from occurring in goaf zones. One solution is a method presented in this article. It aims at determining an area in goaf zones, where an endogenous fire may occur. The study focused on the longwall ventilated with the Y system. This area was determined based on two criteria, namely air velocity and oxygen content. The study was carried out for various volumes of air supplied to the longwall. Therefore, the purpose of the study was to develop research methodology and determine the location of an area at the risk of an endogenous fire. The location of this area was determined for three different volume expenditures of air supplied to the longwall ventilated with the Y system.

**Keywords:** endogenous fire, mining operation, "Y" longwall ventilation system, goaf