Numerical Research of Oxidation Zone Variation in Goaf of Longwalls U-Type System from Borders and U-Type System to the Borders Ventilated

Numerical Research of Oxidation Zone Variation in Goaf of Longwalls U-Type System from Borders and U-Type System to the Borders Ventilated

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Abstract. Endogenous fires are significant hazard in the Polish and global underground mining industry. These fires are result of spontaneous combustion of coal due to the inability to discharge heat from the oxidation process. One of the main places of occurrence of endogenous fires are goaves in longwalls. By endogenous fire we mean self-ignition of coal, caused by a process of self-heating of coal (leading to increase in temperature), and under endogenous fire hazard possibility of coal self-ignition as a result of its self-heating process in mining heading or its surroundings. Hazard of endogenous fires in these goaves are formed due to the airflow with determined velocity and specified chemical constitution. The velocity of air stream mainly depends on the type of rocks forming the stroke and applied longwall ventilation system. In the paper results of numerical research of airflow through goaves ventilated in U-type system from borders and U-type system to the borders are presented. The aim of the analysis was to determine in these goaves a oxidation zone. For determined mining-geological conditions, the critical value of velocity of airflow and oxygen concentration in goaves, conditioning initiation of coal oxidation process were determined. Modelling studies carried out basing on the developed methodology included in its scope the study of spatial models of exploitation longwalls being ventilated on the U-type system from the borders and U-type system to the borders and its goaves. Results of tests and analyses, as well as conclusions presented in this article should be a valuable source of knowledge, and could be used in the practice of choosing exploitation longwall ventilation system and ventilation parameters of the air.

1. Introduction

The endogenous fire hazard is one of the most common and widespread threats to occupational health and safety in hard coal mines in Poland and worldwide [1, 2, 3,4]. The endogenous fire hazard means that there is a risk of spontaneous combustion of coal due to the process of its self-heating in a mine working or the vicinity.

The endogenous fire hazard may therefore be regarded as one of the most dangerous and common ventilation-related risks. In the years 2007–2017, there were as many as 67 endogenous fires, 33 of which were located in caving goaves of longwalls [5].

The goaves of longwalls with caving, occurring due to the collapse of roof rock layers, create a porous bed which allows gases to flow through because of the presence of void spaces (crevices between the collapsed blocks of roof rocks) [6,7, 8, 9, 10]. If, during the exploitation process, coal has been left in the roof or floor layer of the exploited bed, or there are patches of coal or its subeconomic resources in the rocks lying over this bed, the caving will push the coal into the goaves, turning it into a source of endogenous fires. Crushed coal left in the goaves and the air flowing through them at a dangerous speed, as well as an adequately high oxygen concentration, are key determinants of the coal self-heating.

During longwall ventilation, part of the fresh air stream makes its way into the caving zone, thus posing a risk of coal oxidation being initiated. This process in goaves occurs in areas which meet the necessary conditions for its initiation. Such areas could be termed as the zones with a particularly high risk of endogenous fires. It is practically impossible to demarcate the zone with a particularly high risk of endogenous fires in underground conditions because it is formed in inaccessible locations, thereby preventing any real examinations [1, 2, 3, 9, 10].

The paper presents the results of numerical tests which aimed at demarcating such a zone in the caving goaves of a longwalls ventilated with U-type system from borders and U-type system to the borders. The tests were conducted using Computational Fluid Dynamics (CFD), with related calculations performed by means of the ANSYS Fluent programme, based on the Finite Volume Method (FVM). The tests were used to specify the physical and chemical parameters of the air flowing through the goaves with caving, treated as a porous medium. The boundary values for these parameters, responsible for the commencement of coal self-heating, were also determined. This served as the basis for determining the position of the zone with a particularly high risk of endogenous fires in the goaves with caving. The results obtained may represent a significant source of information on the identification of sites with a potential likelihood of endogenous fires in goaves with caving and, at a later stage, make it possible to select a proper preventative method.

2. Mathematical model of gas flow

The airflows at the maingate, tailgate and longwall are simulated as fully developed turbulent flow by using an *k-ε* model. Because laminar flow, transition flow and turbulent flow coexist in the goaf, the flow through the gob is treated as a non-darcy flow. For porous material analysis, like a goaf with caving, can be also used model of foam structures with open cells presented in [11].

2.1. Basic flow equations

System of balance equations of mass, momentum and energy (equations of fluid handling) of one-component flow takes the following form [12]:

$$\frac{\partial}{\partial t}(\rho) + div\left(\rho \vec{v}\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) + div\left(\rho \vec{v}\,\vec{v}\right) = div\left(-p\overset{\leftrightarrow}{I} + \overset{\leftrightarrow m}{\tau} + \overset{\leftrightarrow t}{\tau}\right) + \rho \vec{s}_p \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) + div\left(\rho e \vec{v}\right) = div\left[\left(-p\overset{\leftrightarrow}{I} + \overset{\leftrightarrow m}{\tau} + \overset{\leftrightarrow t}{\tau}\right)\vec{v} + \overset{\to m}{q_s} + \overset{\to t}{q_s}\right] + \rho s_e \tag{3}$$

System of equations (5-7) in a vector form can be written as [8]:

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho \\ \rho \vec{v} \\ \rho e\end{pmatrix} + div\begin{pmatrix}\rho \vec{v} \\ \rho \vec{v}\,\vec{v} + p\overset{\leftrightarrow}{I} \\ \rho e \vec{v} + p\overset{\leftrightarrow}{I}\vec{v}\end{pmatrix} = div\begin{pmatrix}0 \\ \overset{\leftrightarrow m}{\tau} + \overset{\leftrightarrow t}{\tau} \\ \left(\overset{\leftrightarrow m}{\tau} + \overset{\leftrightarrow t}{\tau}\right)\vec{v} + \overset{\to m}{q_s} + \overset{\to t}{q}\end{pmatrix} + \begin{pmatrix}0 \\ \rho \vec{s}_p \\ \rho s_e\end{pmatrix} \tag{4}$$

Variables presented in the system of equation (5-8) are [8]:

$$\left\{\rho, \vec{v}, p, \overset{\leftrightarrow m}{\tau}, \overset{\leftrightarrow t}{\tau}, \vec{s}_p, e, s_e, \overset{\to m}{q_s}, \overset{\to t}{q_s}\right\} \tag{5}$$

where: p is the static pressure (Pa), V_x, V_y and V_z are the air velocity (m/s), C_1 is the factor of viscous resistance (1/m^2), C_2 is the factor of inertial resistance (1/m), ρ is the fluid density (kg/m^3).

In a case of modelling of flow through the porous medium such as goaf with caving, infiltration of presented system of equations is possible by introducing into balance equations additional factors.

This factor influences on macroscopic increase of movement resistance. The movement resistances brake momentum of fluid flowing through porous medium and acting on hole volume ot this medium. In such conception part of balance momentum equation should be modified.

Source of resistance can be in a form of Forchheimer eqaution which in three-dimensional space has a form [13]:

$$-\frac{\partial p}{\partial x} = C_1 \mu V_x + C_2 \frac{1}{2} \rho |V| V_x \tag{6}$$

$$-\frac{\partial p}{\partial y} = C_1 \mu V_y + C_2 \frac{1}{2} \rho |V| V_y \tag{7}$$

$$-\frac{\partial p}{\partial z} = C_1 \mu V_z + C_2 \frac{1}{2} \rho |V| V_z \tag{8}$$

Combined with Eq. (10)-(12), the viscous resistance coefficient C_1 and the inertial resistance coefficient C_2 in ANSYS Fluent are determined from the dependence:

$$\begin{cases} C_1 = \dfrac{1}{k} \\ C_2 = \dfrac{2\beta D_m}{kn} \end{cases} \tag{9}$$

2.2. Model of air leakage resistance coefficient in the goaf

Nonlinear equation of movement describes filtration (flow) in porous medium given by Bachamt, has a form [13]:

$$-h = (a + b|V|)\vec{V} \tag{10}$$

where: h is the pressure head (m), V *is* the fluid velocity (m/s), a and b are scalar coefficients in Eq. (14) and can be expressed by Eq.(15):

$$\begin{cases} a = v/(g \cdot k) \\ b = \beta \cdot D_m /(g \cdot n \cdot k) \end{cases} \tag{11}$$

where: g is the acceleration of gravity (9.81 m/s^2), n is the porosity, v is the kinematic viscosity (m^2/s), k is the permeability of porous media (m^2), β is the shape factor of the media particles (1.5) and D_m is the harmonic average particle size (0.1 m).

The porosity can be obtained by K, which is the coefficient of the bulk increase of caving rocks in the goaves [13]:

$$n(x, y, z) = 1 - \frac{1}{K(x, y, z)} \tag{12}$$

3. Characteristic of investigated system

Model-based tests were conducted for the longwalls U-type system from borders and U-type system to the borders ventilated. The purpose was to demarcate the zone with a particularly high risk of endogenous fires in the caving goaves of this longwalls.

The geometrical model of a longwall ventilated with the U-type system from borders and its goaves with caving has been presented in Figure 1a, while that of a longwall ventilated with the and U-type system to the borders – in Figure 1b.

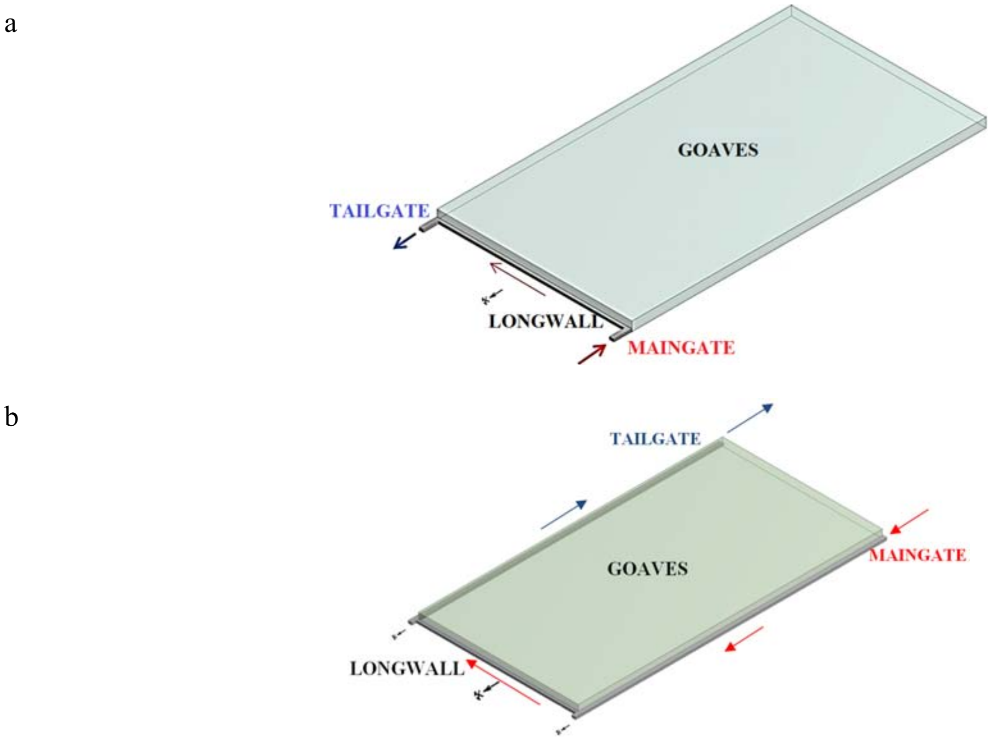

Figure 1. Geometrical model of investigated system of excavations U-type system from borders (a) and U-type system to the borders ventilated (b)

The geometrical model of a longwall ventilated with the U-type system from the exploitation field borders incorporates:

- sections of longwall galleries with a length of 20.0 m and a cross sectional area of A = 15.0 m^2,
- 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 400.0 m (constituting ⅔ of the longwall panel length).

The geometrical model of a longwall ventilated with the U-type system to the exploitation field borders incorporates:

- sections of longwall galleries with a length of 20.0 m and a cross sectional area of A = 15.0 m^2,
- a maingate maintained along the goaves with caving, with a length 405.0 m,
- a tailgate maintained along the goaves with caving, with a length 405.0 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 400.0 m (constituting ⅔ of the longwall panel length).

The range of the vertical air flow zone was 3.5 times the height of the exploited seam for both geometrical models.

Such geometrical models were subjected to the process of discretization. The geometrical models failed to incorporate the machinery and devices of the longwall as well as the tailgate and maingate equipment.

The simplifications adopted in the models developed, in relation to the real-world models, constitute a certain compromise between the calculation precision and the time of obtaining a solution.

4. Results and discussions

Performed tests enabled to determine distributions of physical and chemical parameters of air stream flowing through the tested headings and goaves with caving. Distributions of air velocity, dangerous velocity and oxygen concentration in goaves with caving at distance 2.0 m from exploited seam floor were presented in Figures 2, 3 and 4 for analyzed ventilation systems.

a b

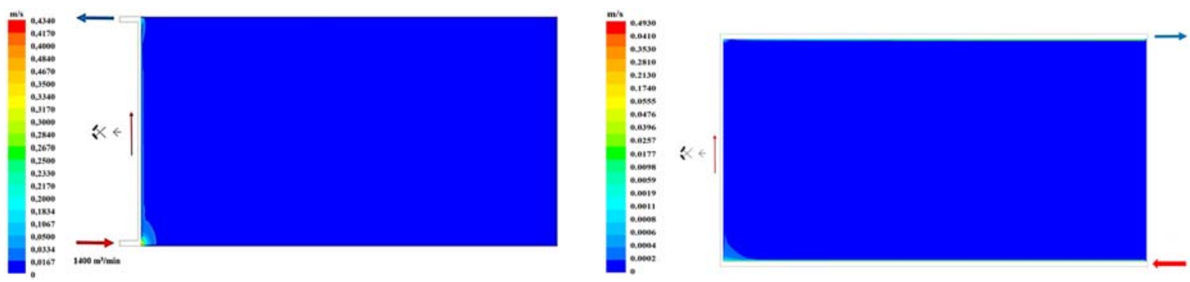

Figure 2. Distributions of air dangerous velocity of air stream flowing through the goaves of longwalls U-type system from borders (a) and U-type system to the borders ventilated (b)

a b

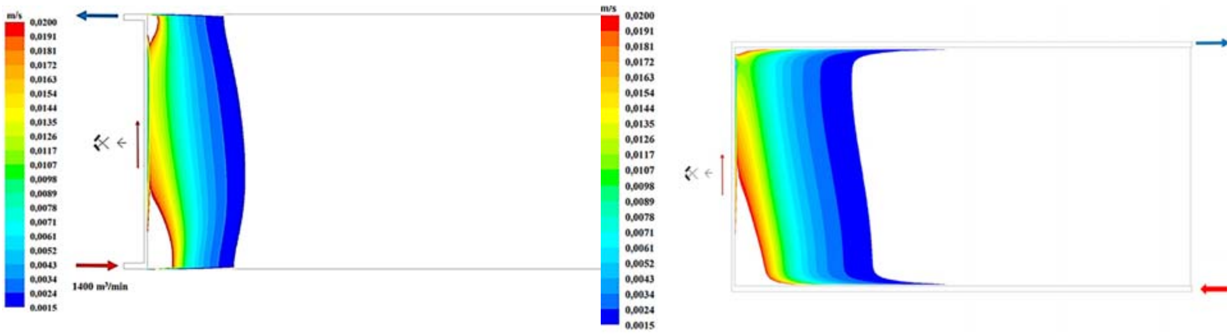

Figure 3. Distributions of air dangerous velocity of air stream flowing through the goaves of longwalls U-type system from borders (a) and U-type system to the borders ventilated (b)

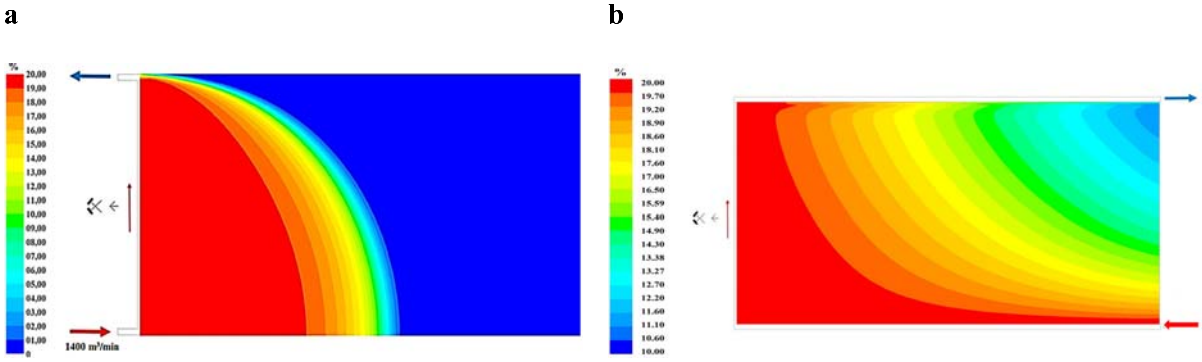

Figure 4. Distributions of oxygen concentration in air stream flowing through the goaves of longwalls U-type system from borders (a) and U-type system to the borders ventilated (b)

Based on the obtained results, characteristics of changes in velocity of air flowing through the goaves with caving (Figure 5) and distributions of oxygen concentrations (Figure 6) present in that air as a function of the distance from the front longwall were determined.

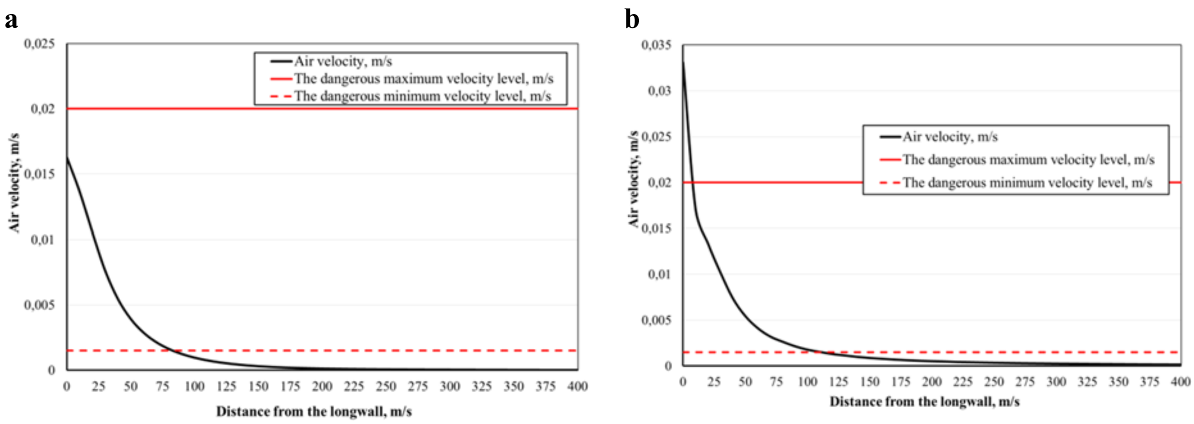

Figure 5. Characteristics of changes of velocity of air flowing through the goaves of longwalls U-type system from borders (a) and U-type system to the borders ventilated (b)

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

For longwall U-type system from borders ventilated, at a distance of up to 84.0 m from the caving line into the depths of the goaves, the speed of the flowing air reaches the critical value in terms of the risk of endogenous fire hazard, i.e. the value from 0.0015 m/s to 0.02 m/s. While for longwall U-type system tot he borders ventilated, at a distance from 13 up to 112.0 m from the caving line into the depths of the goaves, the speed of the flowing air reaches the critical value in terms of the risk of endogenous fire hazard, i.e. the value from 0.0015 m/s to 0.02 m/s.

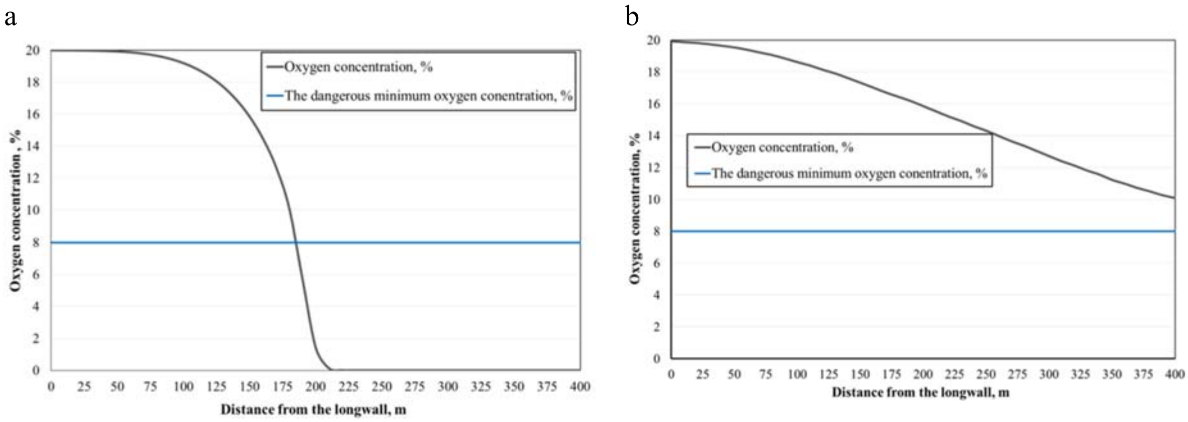

Figure 6. Characteristics of changes distributions of oxygen concentrations in air flowing through the goaves of longwalls U-type system from borders (a) and U-type system to the borders ventilated (b)

Based on the characteristics determined, it can be concluded that the concentration of oxygen in goaves with caving decreases along with the increasing distance from the longwall front. For longwall U-type system from borders ventilated, at a distance of up to 200.0 m from the caving line into the depths of the goaves, oxygen concentration in the air flowing through the goaves with caving reaches the dangerous value in terms of the risk of endogenous fires, i.e. the value higher than or equal to 8%. While for longwall U-type system tot he borders ventilated, at a distance of up to 400.0 m from the caving line into the depths of the goaves, oxygen concentration in the air flowing through the goaves with caving reaches the dangerous value in terms of the risk of endogenous fires.

Taking both characteristics into account, the zone with a particularly high risk of endogenous fires for longwalls U-type system from borders and U-type system to the borders ventilated was demarcated in the its goaves.

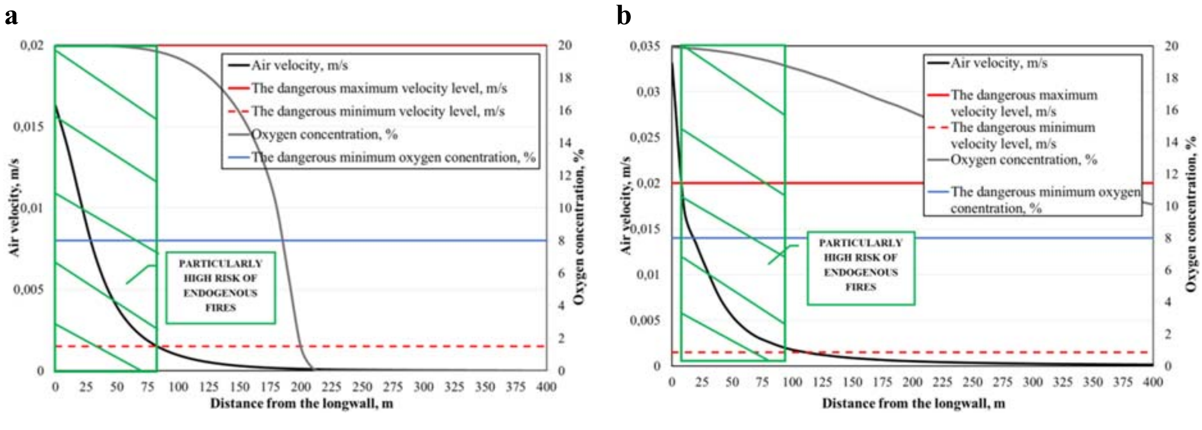

Figure 7. Particular high risk of endogenous fires goaves with caving for longwalls U-type system from borders (a) and U-type system to the borders ventilated (b)

Table 1 presents the range of the zone with a particularly high risk of endogenous fires for longwalls ventilated with the U-type system from the exploitation field borders and with U-type system up to the exploitation field borders, with the volumetric flow rate of the air flowing through a longwall equal to 1400 m^3/min.

Table 1. The range of the zone with a particularly high risk of endogenous fires in caving goaves.

Longwall ventilation systems	Critical air velocity zone, m	Critical oxygen concentration zone, m	The zone with a particularly high risk of endogenous fires, m
U-type system from the exploitation field borders	0 – 84.0	0 – 200.0	0 – 84.0
U-type system to the exploitation field borders	13.0 – 112.0	0 – 400.0	13.0 – 112.0

5. Conclusions

The article presents the results of numerical tests, whose purpose was to determine the zone with a particularly high risk of endogenous fires in goaves with caving for longwalls U-type system from borders and U-type system to the borders ventilated. Model developed and used for flow analysis of mixture of air stream and mining gases through the goaf with caving enabled to determine the distribution of physical and chemical parameters of this mixture for longwalls U-type system from borders and U-type system to the borders ventilated.

Obtained results enabled to determine of zones particularly endangered by endogenous fires in goafs, in which velocity of airflow equals from 0.0015 m/s to 0.02 m/s, oxygen concentration – min. 8%. Based on that, one can conclude, that location and range of this zone in significantly way depends on a longwall ventilated system. On the basis of the results obtained, it can be concluded that the longwall ventilation system in use have a significant impact on the speed of the air flowing through goaves as well as on the value of oxygen concentration in this air.

Comparing the test results obtained for both ventilation systems under analysis, one may conclude that the range of the zone with a particularly high risk of endogenous fires for the U-ventilation system to the borders is significantly greater than that for the U-type system from the borders. Knowledge of range of this zone has very important practical meaning. It allows to take preventive actions, in order to prevent occurrence of endogenous fire.

Obtained results indicate, that numerical methods can be successfully used for variant analyses of processes connected with ventilation of underground mine headings, including analyses connected with airflow through the goaf, and also in the analyses of emergency states, like initialization of oxidation process in favorable conditions leading to self-heating and self-ignition. Therefore, it can be assumed that simulation methods based on computational fluid dynamics (*CFD*) could be significant tool in improvement of the occupational safety in the mining.

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References

[1] J. Brodny and M. Tutak, "The impact of the flow volume flow ventilation to the location of the special hazard spontaneous fire zone in goaf with caving of operating longwalls", *16th International Multidisciplinary Scientific GeoConference. SGEM 2016*, 978-619-7105-56-8, pp. 897-904, DOI: 10.5593/SGEM2016/B12/S03.115

[2] J. Brodny and M. Tutak M, "Analysis of gases emitted into the atmosphere during an endogenous fire". *Proceedings of 16th International Multidisciplinary Scientific GeoConference SGEM 2016*, pp. 75-82. DOI: 10.5593/SGEM2016/HB43/S06.011.

[3] J. Brodny and M. Tutak M, "Determination of the Zone with a Particularly High Risk of Endogenous Fires in the Goaves of a Longwall with Caving", *Journal of Applied Fluid Dynamics*, Vol. 11, No. 3, pp. 545-553. DOI: 10.18869/acadpub.jafm.73.246.27240

[4] Y. J. Song, " Defending and Extinguishing Fire by Even Air Pressure in Mine", *Beijing: The Press of Coal Industry*, 2002, pp. 260-262.

[5] WUG. “The state of occupational health and safety in the mining industry”. Katowice 2007-2017, http://www.wug.gov.pl/.

[6] C.O. Karacan, “A Methodology for Determining Gob Permeability Distributions and Its Application to Reservoir Modeling of Coal Mine Longwalls”, 2007 *SME Annual Meeting and Exhibit*, Denver, Colorado, February 25–28, preprint 07-78. NIOSHTIC-2 No. 20031652. Littleton, Colorado: Society for Mining, Metallurgy, and Exploration.

[7] A. Lisowski, “The direction of the operation longwall with caving”, Prace GIG, Komunikat nr 2001, Katowice 1959.

[8] V. Palchik, “Influence of physical characteristics of weak rock mass on height of caved zone over abadoned subsurface coal mines”, *Environmental Geology*, vol. 44, Issue 1, 2003, pp 92–101, DOI: 10.1007/s00254-002-0542-y.

[9] J. Brodny and M. Tutak M., “Analysis of methane emission into the atmosphere as a result of mining activity”. *Proceedings of 16th International Multidisciplinary Scientific GeoConference SGEM 2016*, pp 83-90. DOI: 10.5593/SGEM2016/HB43/S06.012.

[10] J. Brodny and M. Tutak M., “Analysis of methane hazard conditions in mine headings”. *Tehnički vjesnik/Technical Gazette*, Vol. 25/No.1, pp. 271-276. DOI:10.17559/TV-20160322194812.

[11] A. John. , M. John. M. and A Bartela., “Numerical homogenization of the foamed metal structures”, *J. Mechanika.* 2016 vol. 22 No. 5. pp. 343-348. DOI: 10.5755/j01.mech.22.5.16689.

[12] W. Sobieski, “The basic equations of fluid mechanics in form characteristic of the Finite Volume Method”, *Tech Sci* 2011, 14(2), 299-313.

[13] Z.Q. Di, G.X Ding and S.X. Zuo., “The theoretical calculation and observation analysis of the “Three Zones” in the goaf of fully mechanized face with top coal drawing.” *J. China Univ. Min. Technol*. 1993, 22 (1). 8-16.