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Determination of the Zone with a Particularly High Risk of Endogenous Fires in the Goaves of a Longwall with Caving

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ABSTRACT

During ventilation of longwalls, part of the air stream migrates into goaves with caving. In the case where these goaves contain coal susceptible to spontaneous combustion, such air flow through the goaves may lead to the formation of favourable conditions for coal oxidation and, subsequently, for its self-heating and spontaneous combustion. The ensuing endogenous fire may constitute a serious hazard to the mining crew and underground operations. The article presents the results of a numerical analysis of air stream flowing through the goaves of a longwall with caving ventilated with the U-type system from the exploitation field borders. The purpose of the analysis was to demarcate the zone with a particularly high risk of endogenous fires within the goaves. The hazardous values of air flow speed and oxygen concentration in the goaves, responsible for the commencement of low-temperature coal oxidation, were determined for specific mining and geological conditions

Keywords: CFD; Endogenous fire; Longwall; Goaves; Underground coal mine.

NOMENCLATURE

ρ	fluid density
a	empirical factor depending on the mining-geological conditions goaves
C_2	inertial resistance factor
$D_{i,m}$	the mass diffusion coefficient for species „i“ in the mixture
F	the external body force
g	the gravitational body force
G_b	generation of turbulence kinetic energy due to buoyancy
G_k	the generation of turbulence kinetic energy due to the mean velocity gradients
Ji	the diffusion flux of species „i”
k_0	permeability coefficient of goaves behind the front of the longwall
l	total length of the longitudinal longwalls
m_i	thickness of particular layers roof rocks
p	static pressure
r_0	empirical factor depending on the mining-geological conditions goaves
R_i	the net rate of production of species „i“
R_{rri}	tensile strength of the rock layers
R_{rrs}	resistance of roof rock stratification
Sct	the turbulent Schmidt number
S_i	the rate of creation by addition from the dispersed phase plus any user-defined sources
t	time
u, v, w	directions velocity
Y_i	the local mass fraction of each species
Y_M	contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
τ	the stress tensor
μ_g	the coefficient of dynamic viscosity of air
μ_t	the turbulent viscosity
σ_k	turbulent Prandtl numbers for k
σ_ε	turbulent Prandtl numbers for ε

1. INTRODUCTION

In underground hard coal mining, there is a series of phenomena that endanger the safety of work and exploitation (Brodny *et al.* 2015, Brodny *et al.* 2016a, Brodny *et al.* 2016b). These phenomena primarily result from natural hazards and constitute a significant source of risk, leading to both human and material loss. The leading position in this group is occupied by the endogenous fire hazard. Endogenous fire should be understood as spontaneous combustion of coal caused by the self heating process (leading to a rise in temperature), while the endogenous fire hazard as the possibility for spontaneous combustion of coal due to its self heating in or close to a mine heading. Spontaneous combustion of coal is caused by its oxidation in air, at ambient temperature. The oxidation process is supported by the ability of coal to absorb oxygen, with simultaneous release of heat. If the heat from the oxidation reaction is not carried away, the temperature will be on a constant rise, thereby leading to spontaneous combustion of coal left in the goaf with caving. The self heating of coal itself is thus a process of its oxidation, even at low temperatures. It can therefore be assumed that spontaneous combustion is a process of uncontrolled temperature rise as a result of coal oxidation (Jiang *et al.* 1998, Liu *et al.* 1998, Dai *et al.* 2012, Brodny *et al.* 2016b).

As a consequence of an endogenous fire, the mining atmosphere is filled with a very dangerous product, namely carbon monoxide (Brodny *et al.* 2015). The presence of this gas makes the atmosphere extremely hazardous for the crew to work in. Moreover, an endogenous fire causes a risk of methane combustion or explosion (Brodny *et al.* 2015, Brodny *et al.* 2016b).

The endogenous fire hazard may therefore be regarded as one of the most dangerous and common ventilation-related risks. In the years 2007–2017 (up until the third quarter), there were as many as 63 endogenous fires, 30 of which were located in caving goaves of longwalls (Patyńska 2017).

Goaves with caving are a space filled with rock debris, formed after coal has been mined from a given area. The collapsing roof rocks form a porous medium which permits the flow of various types of gases. As a result of underground coal exploitation, there is very little coal left in the floor or roof layers (Palchik 2003, Karacan 2007, Karacan 2010a, Kracan 2010b). However, coal is left in the goaves as they form. They often include the so-called subeconomic coal as well. Its presence in the goaves creates a high endogenous fire hazard.

The crevices (or open contact points between chaotically arranged blocks of rocks) found in goaves with caving make it possible for a mixture of gases (e.g. air and methane) to flow through. This flow results from the pressure compensation of gases, including oxygen, in all empty spaces of the goaves that form a system of interconnected vessels (Lisowski 1959, Song 2002, Palchik 2003, Karacan 2007, Karacan 2010a, Karacan 2010b). The coal left in the goaves and the air flowing at a specific speed and having relevant oxygen concentration are the prerequisites for the self-heating process to begin, thus posing a risk of spontaneous combustion of the coal. Therefore, it can be assumed that the physical and chemical parameters of the air flowing through goaves with caving have a significant impact on the occurrence and development of endogenous fires.

The flow of air through goaves with caving results from the separation of part of the air stream from the ventilation stream supplied when the longwall is being ventilated. This flow is referred to as air filtration and always occurs during ventilation of longwall headings, irrespective of the ventilation system used.

In Polish hard coal mines, more than 75% of active longwalls are ventilated with the U-type system from the exploitation field borders. In this system, fresh air is supplied to the longwall along the maingate while bad air is discharged from the longwall along the tailgate. Maingates are maintained only along the body of coal. Therefore, in this system, the air stream can migrate to goaves with caving only at the inlet of the longwall and along its whole length.

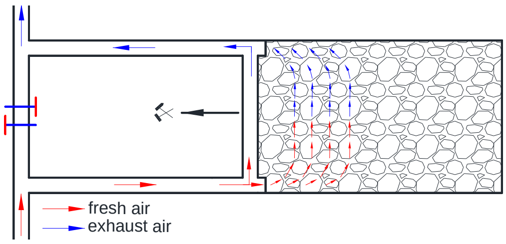

Fig. 1. Scheme of a U-type system from the exploitation field borders.

Despite the small surface area through which air can migrate from a longwall to goaves with caving, there is a great threat that coal oxidation will be initiated. However, the oxidation process, leading to the self-heating and spontaneous combustion of coal, will occur only in the area where favourable conditions exist. This area is referred to as the zone with a particularly high risk of endogenous fires in goaves with caving. In underground conditions, it is practically impossible to demarcate this zone. This is due to its inaccessibility, which excludes the possibility of carrying out any real-world tests. However, the extremely negative consequences of endogenous fires require actions to be taken in order to identify this zone. Such possibilities are offered by numerical methods, which are increasingly used for the analysis of mining ventilation issues.

The authors of the paper decided to extend the applicability of these methods and use them for the assessment of the endogenous fire hazard in goaves with caving as well as for the demarcation of the zone with a particularly high risk of these fires.

The paper present the results of numerical tests which aimed at demarcating such a zone in the caving goaves of a longwall ventilated with the U-type system from the field 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. Criterion On Endogenous Fire Hazard

The initiation of the low-temperature oxidation reaction of coal, leading to its self-heating and spontaneous combustion, requires the presence of oxygen. Coal oxidation releases heat whose accumulation causes an increase in the temperature of the coal left in goaves, thereby causing its spontaneous combustion. The process of heat accumulation is strictly dependent on the speed of the air flowing through goaves with caving, while the oxidation process – on oxygen concentration in this air (Liu *et al*. 1998, Yang *et al*. 2000, Cui 2002a). It should therefore be assumed that the process of coal self-heating, leading to its spontaneous combustion, depends on specific physical and chemical parameters of air.

The most significant physical parameter of air affecting the accumulation of heat is the speed it reaches while flowing through goaves with caving. The tests performed demonstrated that the dangerous speed of air stream resulting in the self-heating of coal ranges from 0.02 to 0.0015 m/s. If this speed is lower than 0.0015 m/s, the process of coal self-heating will not be initiated. On the other hand, if this speed is higher than 0.02 m/s, the process of heat accumulation will not occur (it will be dissipated) (Cui 2002, Gao *et al.* 2010a, Gao *et al.* 2010b, Dai *et al*. 2012). As a result, in terms of the air flow speed values, one can distinguish the following zones in goaves with caving: the cooling zone, the zone with a particularly high risk of endogenous fires and the suffocation zone.

Due to the oxygen content in the air stream flowing through goaves, its concentration level becomes hazardous upon exceeding the value of 8%. The zone with a particularly high risk of endogenous fires occurs when the oxygen concentration level is equal to or higher than 8%, while the oxygen-poor zone – at concentrations below 8% (Cui 2002, Gao *et al.* 2010a, Gao *et al.* 2010b, Dai *et al.* 2012).

Table 1 provides a summary of the boundary values for the physical and chemical parameters of the air stream flowing through goaves, typical of the zone with a particularly high risk of endogenous fires as well as of the cooling zone and the oxygen-poor (suffocation) zone.

Taking into consideration the physical and chemical parameters of the air stream flowing through goaves with caving, the following criterion was formulated for the endogenous fire hazard in these goaves.

Table 1 The boundary values for the parameters of the air stream flowing through goaves

The zone	Air speed, m/s	Oxygen concentration, %
Cooling	$0.02 < v$	$O_2 \geq 8$
Particularly high risk of endogenous fires	$0.02 \geq v \geq 0.0015$	$O_2 \geq 8$
Suffocation	$v < 0.0015$	$O_2 < 8$

Therefore, one can formulate following criterion of hazard of endogenous fire in goaves:

– the presence of crushed coal, remaining in goaves prone to self-heating,

– velocity of airflow through goaves,

– min. 8% of oxygen concentration in the air flowing through goaves.

3. Mathematical Model Of Flow

A flow of air stream through a longwall, tailgate and maingate is simulated as a flow of turbulent nature. However, there are three co-existing types of flows in goaves, namely laminar, transient and turbulent. The flow in this part of the area under examination is treated as non-Darcy flow.

Issues connected with transport of fluid are solved basing in the following fluid mechanics equations (Veersteg *et al.* 2007):

1. The continuity equation:

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

2. The momentum equation:

$$\frac{\partial}{\partial t}(\rho v)+\nabla\cdot(vv)=-\nabla p+\nabla\tau+\rho g+F \tag{2}$$

The basis for a mathematical description of the transportation process of methane released into underground headings is the principle of mass conservation referred to this gas. The mathematical model of transportation, being a set of advection–diffusion equations, which for *i*- of this substance *i*=1,….n, assumes the following form:

3. The species transport equation:

$$\frac{\partial}{\partial t}(\rho Y_i)+\nabla\cdot(\rho v Y_i)=-\nabla\cdot J_i+R_i+S_i \tag{3}$$

4. The mass diffusion:

$$J_i=-(\rho D_{i,m}+\frac{\mu_t}{Sc_t})\nabla Y_i \tag{4}$$

Airflow through the goaves is a flow through the porous medium. Therefore, to the equation of conservation of momentum, an additional source member Si describing this flow was introduced:

$$S_i = -\left(\frac{\mu_g}{k} + C_2 \frac{1}{2} \rho_g |v| v\right) \tag{5}$$

The loss of momentum expressed by the above equation generates, in the porous control volumes, a pressure gradient which is proportional to the speed or the square of speed in each volume of fluid.

The flow of air stream through a longwall and caving goaves located immediately behind the sections of the powered roof support, where no full caving has occurred (terms as the so called caving step), does not correspond to the laminar flow.

This flow features irregular movements of the air stream particles, and the parameters of this flow undergo unpredictable random changes in space and time. A characteristic phenomenon for this type of flow is the occurrence of vortices of different sizes.

In the turbulence model *k–ε*, 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:

$$\rho \frac{\partial k}{\partial t} + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{6}$$

$$\rho \frac{\partial \varepsilon}{\partial t} + \frac{\partial}{\partial xi}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon\rho}\frac{\varepsilon^2}{k} + S_\varepsilon \tag{7}$$

4. THE PERMEABILITY OF GOAVES

The permeability of caving goaves in a longwall allows for the flow of gases and depends on the type of roof rocks forming these goaves as well as on the distance from the longwall front. This permeability is determined by means of the permeability coefficient. The value of this coefficient for goaves with caving depends on the type of roof rocks forming the goaves and their stratification resistance. The stratification resistance is the specific loosening resistance acting against the force of gravity (Szlązak 2001). It defines the natural ability of the rock mass to resist stratification and caving of the roof rocks into the space of the mine heading. It can be determined from the following formula (Szlązak 2001):

$$R_{rrs} = \frac{\sum_{i=1}^{n} R_{rri} \cdot m_i}{\sum_{i=1}^{n} m_i} \tag{6}$$

The stratification resistance of roof rocks thus calculated makes it possible to determine the permeability coefficient of goaves with caving:

$$k(x) = \frac{\mu_g}{r_0 + ax^2} \tag{7}$$

for $0 \le x \le 2/3 \cdot l$

and from dependence:

$$k(x) = \frac{\mu}{r_0 + a\left(\frac{4}{3}l - x\right)^2} \tag{8}$$

Formulae 8 and 9 include empirical coefficients r_0 and a, whose value is dependent on the stratification resistance value of the roof rocks forming the given caving.

The value of the coefficient r_0 is determined from the following formula:

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

while the value of the coefficient a is calculated from the following equation:

$$a = 6 \cdot 10^9 R_{rrs}^{-1{,}74} \tag{10}$$

On the other hand, the value of the permeability coefficient k_0 is determined on the basis of the equation below:

$$k_0 = \frac{\mu_g}{6} \cdot 10^{-10} R_{rrs}^{1{,}44} \tag{11}$$

5. CHARACTERISTIC OF INVESTIGATED SYSTEM

Model-based tests were conducted for the C-13 longwall in seam 415, in layer 1. The purpose was to demarcate the zone with a particularly high risk of endogenous fires in the caving goaves of this longwall.

5.1. Characteristics Of Geological and Mining Conditions Of The C-13 Longwall Exploited In Seam 415

The C-13 longwall in seam 415 was exploited by a longitudinal system with a roof fall from the exploitation field borders, at the depth of 1,050.0 m, and its mining parameters were as follows:

– length of the longwall 234.0 m,

– height of the longwall 573.0 m,

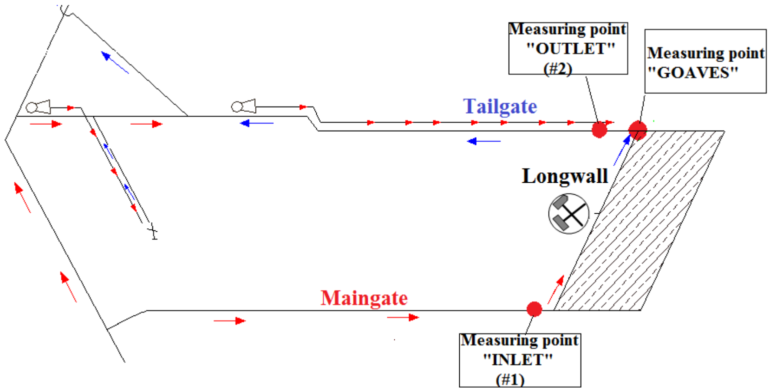

Fig. 2. The longwall ventilation scheme.

Table 2 The results of measurements of the physical parameters of the air

Series	The air velocity, m/s		The pressure kPa		The volume of flow, m/s	
	The point of measurement					
	1	2	1	2	1	2
1	1.91	3.16	109.00	108.07	18.0	24.2
2	1.96	3.10	109.60	108.04	18.4	23.7
3	1.41	3.38	109.21	108.24	19.0	23.7
4	1.35	3.44	109.18	108.25	18.2	24.1
5	1.88	3.05	107.97	107.92	18.2	23.3
6	1.90	3.14	107.96	107.01	19.0	24.6
7	1.62	3.42	108.26	107.46	20.1	25.8
8	1.58	3.39	108.27	107.50	20.3	24.6
9	1.75	3.25	109.16	108.31	20.8	23.8
10	1.70	3.19	109.16	108.31	20.2	23.2

– transverse slope 4°,

– longitudinal slope 8°.

The longwall was mined in the following conditions:

– third category of methane hazard,

– first group of coal susceptibility to spontaneous combustion,

– class-B coal dust explosion hazard.

The roof of the exploited seam contained deposits of silty shales with coal laminations as well as shales with coal having a total thickness of up to 5.9 m. Over these rocks, there was a layer of fine-grained sandstone with a thickness of up to 15.0 m. The floor of the exploited seam contained only silty shale deposits.

The stratification resistance of roof rocks lying in goaves with caving, as determined from equation (9), has the value of 4.02 MPa. The longwall under examination was ventilated by means of the U-type system.

In a Fig. 2 there is presented scheme of longwall ventilation with indicated line of air distribution.

While the longwall was being exploited, air was supplied to it through the maingate at the average rate of approximately 1,153 m^3/min. Due to a high methane hazard in the outlet area of the longwall, an additional air stream (approximately 296 m^3/min.) was also supplied through the air duct installed in the tailgate. The release of methane from the goaves and the exploited body of coal occurred at the average rate of 5.6 m^3/min., and the average value of its concentration at the outlet from the tailgate during exploitation was 0.31%.

5.2. Tests In Underground Conditions

The model-based tests were conducted using the results of tests under real-world conditions for selected physical parameters of the air stream flowing through the longwall area. The tests carried out under in-situ conditions made it possible to specify the boundary values for the numerical model. They encompassed the designation of measuring points situated at the inlet to and outlet from the longwall as well as the measurements of the pressure and speed of air and of the cross-sections of the mine headings. The distribution of measuring points (stations) has been shown in Fig. 3. Table 2 shows the results of the measurements of the air stream parameters in the area under examination, while Table 3 presents the concentrations of carbon monoxide and methane depending on the advance of the longwall. This table also specifies fire prevention measures. Real-world and model-based tests were carried out for the longwall panel length of 375.5 m.

6. THE RESULTS

The model-based tests of air flow through the

Table 3 The results of measurements of the chemical parameters of the air in goaves

Time of the longwall start, m	Face run, m	Progress, m	CO, ppm	CH_4, %
1	573.0	-	-	0.13
2	561.5	11.5	6	0.07
3	531.5	30.0	20	0.24
4	496.5	35.0	57	0.26
5	466.0	30.5	63	0.34
6	443.5	22.5	67	0.18
7	400.5	43.0	75	0.41
8	351.0	49.5	59	0.45
9	294.0	57.0	71	0.45
10	257.5	36.5	87	0.4
11	221.0	36.5	65	0.36
12	196.5	24.5	79	0.32

caving goaves of the C-13 longwall made it possible to determine the distributions of the physical and chemical parameters of air. Given the purpose of the tests, attention was focused on the speed distributions of the air flowing through the goaves and on the oxygen concentration in this air.

The geometric model of the area under examination has been presented in Fig. 4.

The following assumptions were adopted for the modelling of air flow through the goaves with caving:

– goaves with caving treated as an anisotropic porous medium;

– steady and isothermic flow of incompressible fluid;

– an additional mass source located in the goaves – reflecting the flow of methane through the goaves.

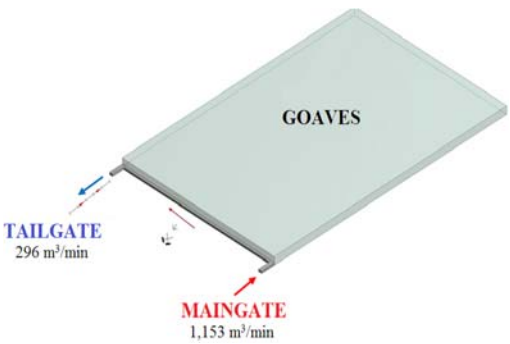

Fig. 3. The geometrical model.

Figure 4 demonstrates the static pressure distribution of the air flowing through goaves with caving, while Fig. 5 presents the speed distribution of this air. Figure 6 illustrates the distribution of the dangerous speed in terms of the endogenous fire hazard, while Fig. 7 shows the oxygen concentration level in the goaves. All these distributions were determined at a distance of 0.5 metre from the floor of the exploited seam. Figures 8 to 11 show the same quantities determined at a distance of 2.5 metres from the floor.

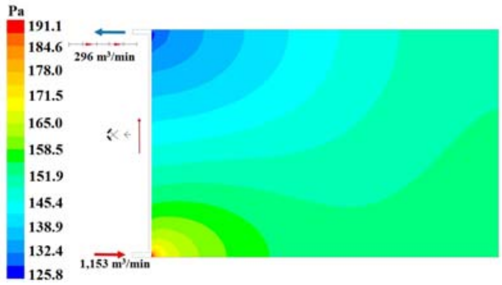

Fig. 4. The static pressure distribution of the air flowing through goaves with caving at distance 0.5 m from exploited seam floor.

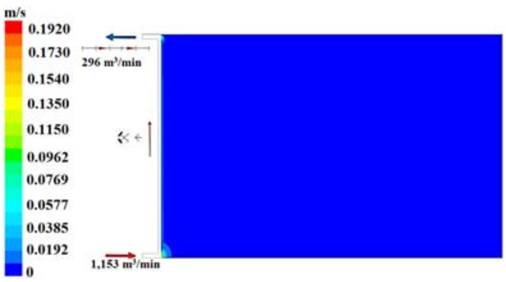

Fig. 5. The speed distribution of the air flowing through goaves with caving at distance 0.5 m from exploited seam floor.

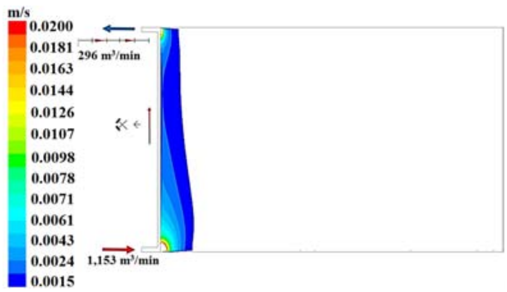

Fig. 6. Distribution of the dangerous speed of the air flowing through goaves with caving at distance 0.5 m from exploited seam floor.

On the basis of the results obtained, it may be concluded that the air speed value decreases along with the increasing distance from the floor of the exploited seam. The highest speed values of this air in the goaves were recorded behind the caving line at the inlet side of the longwall (bottom corner) and at the outlet side of the longwall (upper corner). The highest value of this speed occurred in the bottom corner of the longwall and amounted to 0.34 m/s (at a distance of 2.0 m from the floor).

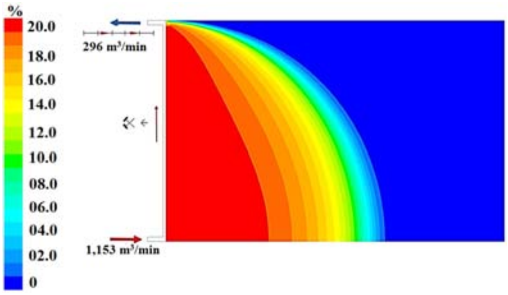

Fig. 7. Oxygen concentration level in the goaves at distance 0.5 m from exploited seam floor.

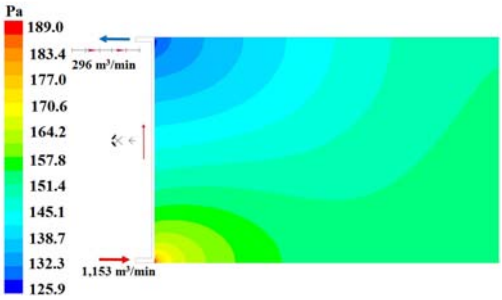

Fig. 8. The static pressure distribution of the air flowing through goaves with caving at distance 2.5 m from exploited seam floor.

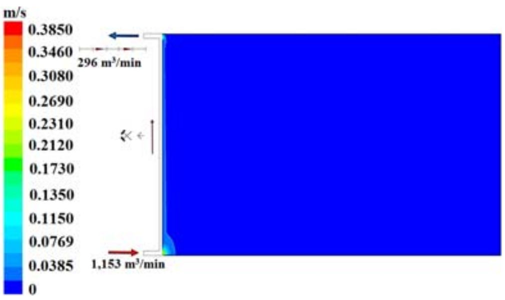

Fig. 9. The speed distribution of the air flowing through goaves with caving at distance 2.5 m from exploited seam floor.

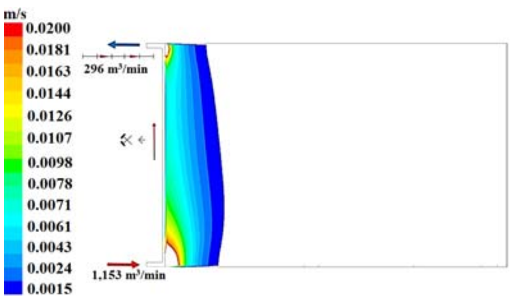

Fig. 10. Distribution of the dangerous speed of the air flowing through goaves with caving at distance 2.5 m from exploited seam floor.

The analysis of the distributions of oxygen concentration in caving goaves indicated that, from the air outlet side (upper corner) of the longwall, the oxygen concentration is lower than from the air inlet side of the longwall (despite additional fresh air being supplied by means of ancillary ventilation equipment).

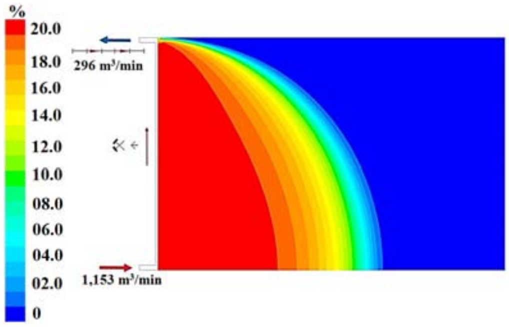

Fig. 11. Oxygen concentration level in the goaves at distance 2.5 m from exploited seam floor.

The results obtained were used for determining the characteristics of the speed changes of the air flowing through the caving goaves of the C-13 longwall in seam 415/1-2, ventilated with the U-type system from the exploitation field borders, and the concentration distributions of the oxygen present in this air.

Figure 12 presents the characteristics of the changing air speed values in the goaves with caving, depending on the distance from the longwall front.

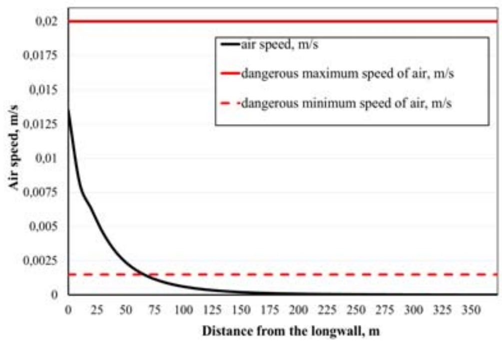

Fig. 12. The characteristics of the changing air speed values in the goaves with caving.

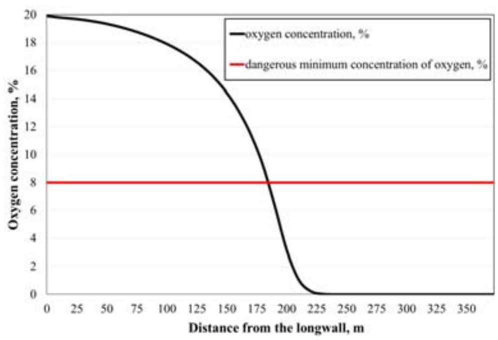

Fig. 13. Distributions of oxygen concentrations in the air flowing through the goaves with caving.

Based on the characteristics determined, it can be

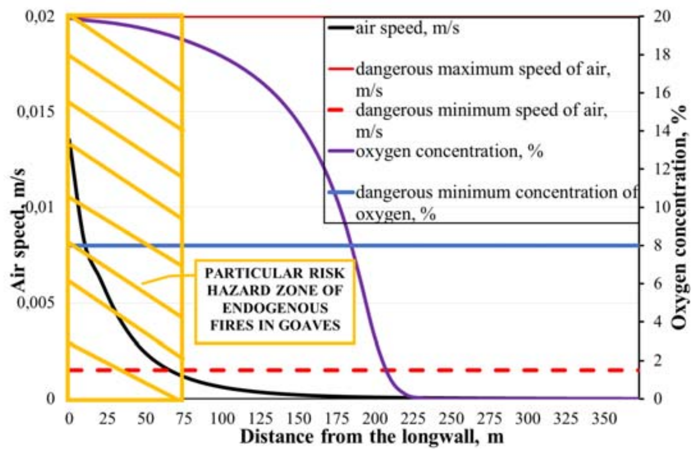

Fig. 14. Particular high risk of endogenous fires goaves with caving.

Table 4 Particular high risk of endogenous fires goaves with caving

Dangerous value of air velocity, m	Dangerous value of oxygen concentration, m	Particular high risk of endogenous fires, m
0–71.0	0–188.0	0–71.0

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 71.0 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 13 presents the changing oxygen concentration values in the air flowing through the goaves with caving, depending on the distance from the longwall front.

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. At a distance of up to 188.0 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%.

Taking both characteristics into account, the zone with a particularly high risk of endogenous fires was demarcated in the goaves of the C-13 longwall. The reach of this zone has been presented in Fig. 15 and Table 4.

The results showed that there is no cooling zone in the caving goaves of the longwall examined. The area in which the air exceeded the speed of 0.02 m/s is small, thereby excluding the occurrence of such a zone in the goaves.

The tests helped to specify that the zone with a particularly high risk of endogenous fires is formed immediately behind the longwall front, and it reaches approx. 71.0 m into the goaves. This zone is an area where the air speed can lead to accumulation of heat in the oxidation zone, and the oxygen concentration in the air flowing through goaves is at least 8%.

7. CONLUSION

The article presents the results of both real-world and numerical tests, whose purpose was to determine the zone with a particularly high risk of endogenous fires in goaves with caving. The numerical model developed on the basis of a real-world longwall made it possible to determine the distributions of air speed and oxygen concentration in this area in the caving goaves of this longwall. The distributions of changes in these parameters allows for demarcating the zone with a particularly high risk of endogenous fires (a zone where coal oxidation occurs), in which the speed of air stream ranges from 0.02 to 0.0015 m/s, and the oxygen concentration level is at least 8%.

The analysis carried out indicated that the speed of the air stream flowing through goaves with caving decreases along with the increasing distance from a longwall. This is the result of decreasing porosity and permeability of such goaves.

A similar phenomenon occurs in the case of oxygen concentration in goaves. This results from the filling of goaves with methane, whose concentration increases along with the growing distance from the longwall front. The model developed, the analyses carried out and the results obtained made it possible to determine the hazardous values of air speed and oxygen concentration in the goaves, thereby allowing for the specification of the size and reach of the zone where the endogenous fire hazard exists. The results are of considerable practical importance since they allow for the development and application of more effective methods for reducing this hazard. This, in turn, should translate into increased safety of the ongoing exploitation as well as into positive economic effects. The example at hand proves that numerical methods can be successfully used for analysing the processes related to the ventilation of underground mine workings. The modelling of goaves with caving as spatial porous media further increases the applicability of these methods. However, it should be emphasised that the reliability of the results obtained requires a precise mapping of the area under examination and a series of underground tests. This is due to the fact that the test results under in-situ conditions determine the boundary conditions adopted, i.e. the quality of the model developed.

REFERENCES

Brodny, J. and M. Tutak (2015). Numerical analysis of airflow and methane emitted from the mine face in a blind dog heading. *Management Systems in Production Engineering* 2/2015, 110-118.

Brodny, J. and M. Tutak (2016a). Analysis of gases emitted into the atmosphere during an endogenous fire. In *Proceedings of SGEM 2016*, 75-82.

Brodny, J. and M. Tutak (2016b). Determination of the zone endangered by methane explosion in goaf with caving of operating longwalls. In *Proceedings of SGEM 2016* 299-306.

Cui, K. (2002). Determination of Spontaneous Combustion Region in Gobs and Numerical Simulation of Air-flowing Field. *Journal of Shandong University of Science and Technology, 21,* 88-92.

Dai, G., S. Zhang and M. Tang (2012). Determination of spontaneous combustion "three zones" in goaf of no.713 fully mechanized longwall of qinan coal mine. *AGH Journal of Mining and Geoengineering* 36, 3.

Gao, J., J. Liu and X. Zhang (2010a). Simulation Study on the Influence of Permeability on Gas Migration in Gob. *China Safety Science Journal* 20(09).

Gao, J. and H. Wang (2010b) Influence of Permeability Distribution on Airflow Field of Leakage in Gob. *China Safety Science Journal* 20(03).

Jiang, S. H. G., R. W. Zhang and K. Y. Chen (1998). Determination of spontaneous combustion three – zone by measuring gas consistency and temperature in goaf. *Journal of China University Mining Technology*. 18,1.

Karacan, C. O. (2010a). A new method to calculate permeability of gob for air leakage calculations and for improvements in methane control. *Proceedings of the 13th U.S./North American Mine Ventilation Symposium,* Sudbury, Ontario, Canada, June 13-16, 2010.

Karacan, C. O. (2010b). Prediction of porosity and permeability of caved zone in longwall gobs. *Transport in Porous Media* 82(2).

Karacan, C. O. (2007). 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.

Lisowski, A. (1959). Direction of exploitation of longwalls with caving (in Polish: Kierunek eksploatacji ścian zawałowych). GIG Works, Statement No 2001, Katowice.

Liu, C., S. Li, Q. Qiao, J. Wang and Z. Pan (1998). Management of spontaneous combustion in coal mine waste tips in China. *Water, Air and Soil Pollution*.

Palchik, V. (2003). Influence of physical charakteristics of weak rock mass on height of caved zone over abadoned subsurface coal mines. *Environmental Geology*, vol. 44, Issue 1.

Patyńska, R. (ed.) (2017). The state of natural and technical hazards in Polish hard coal mines in 2016. GIG, Katowice.

Song, Y. J. (2002). Defending and Extinguishing Fire by Even Air Pressure in Mine. *Beijing:The Press of Coal Indu*stry, 260-262.

Szlązak, J. (2001). The determination of a co-efficient of longwall gob permeability. *Archives of Mining Science* 46, pp. 451–468.

Veersteg K. K. and W. Malalasekera (2007). *An Introduction to Computational Fluid Dynamics. The Finite Volumne Method*. Pearson Education.

Yang, S. Q. and R. W. Zhang (2000). Distribution Regularity of Spontaneous Combustion Three-Zone in Goaf of Fully-Mechanized Coal Faces. *Jouranl of China University of Mining and Technology* 29, 93-96.