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Research paper

Tests of new method of monitoring endogenous fire hazard in hard coal mines

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ABSTRACT

The aim of the article is to present a novel, innovative method of monitoring endogenous fire hazard in hard coal mines, based on a system of temperature sensors placed within solid coal. The developed system of monitoring the level of endogenous fire hazard was tested in an active hard coal mine in Poland. The scope and the method of temperature measurements with downhole temperature sensors in solid coal were presented in detail. Results of systematic temperature monitoring fire prevention activities are presented.

1. Introduction

Endogenous fires in hard coal mines belong to the group of hazards which are harder and harder to monitor and fight (Krause & Smoliński, 2013; Trenczek, 2008; Tutak & Brodny, 2017). The development of an endogenous fire is not a violent process, unlike an exogenous fire, which is caused by external factors. Too late detection of an endogenous fire poses a real threat to the health and life of the personnel working in the area and results in measurable economic losses (Nagornov, Kremcheev, & Kremcheeva, 2019; Snopek, Adamus, & Sancer, 2012; Wojtacha-Rychter & Smoliński, 2018b). Endogenous fires are not limited to longwall goafs. They also develop in driven mine workings, chain pillars between mine workings and goafs, in roadways near fault zones, zones of geological disturbances, in the roof of workings with a remaining coal shelf or coal intercalations and in workings where the coal sidewall is cracked or separated with shotcrete lining. The fire development also depends on the difference in the aerodynamic potential in the vicinity of gateroads, goafs and roadways. It is associated with air permeating through the rock mass both locally and in the whole mining area (Ermakov, Kachurin, & Sencus, 2018). Preventing air permeation through the rock mass is the fundamental assumption of fire prevention in coal mines. The first stage preceding an endogenous fire is the process of coal self-heating. The process is associated with the phenomenon of low-temperature coal oxidation with the oxygen from the mine air. The oxidation process is a highly exothermic process. If the conditions are favourable, the heat emitted in the reaction is accumulated. It leads to coal self-heating and, as a consequence, after exceeding the ignition temperature, to coal self-ignition (Deng, Zhang, Chen, & Luo, 2004; Golynskaya, 2018; Yuan, Restuccia, Richter, & Rein, 2019). It may be concluded that the phenomenon of coal self-ignition is influenced mainly by high proneness of coal to self-heating, sufficient supply of oxygen, and favourable conditions in the rock mass to accumulate heat emitted during the exothermal reaction of hard coal with oxygen from the mine air. If all the three conditions are met, then it may be concluded that there is high probability of self-ignition and, as a consequence, an endogenous fire (Zeng, Dong, & Zhao, 2018). Following the regulations, an underground fire is meant to be: an open flame, substance smouldering or burning with an open flame in an underground mine working, detection of smoke in the mine air or over 25 dm^3/min of carbon oxide in the regional air flow current (Poborowski & Cunningham, 2008).

The occurrence of endogenous fire in a hard coal mine means applying safety procedures, withdrawing the personnel from the area and starting the rescue action. To detect an endogenous fire in underground mines are applied rules specified in mining regulations (Wojtacha-Rychter & Smoliński, 2019).

Firstly, it is the procedure of "Early detection of fires" i.e. collecting air samples in measuring stations and analysing their composition.

As every fire in a mine generates very high economic losses, in the hard coal mining industry there are proper procedures concerning early detection of fires which include fire prevention activities aimed at possibly earliest detection of coal self-heating and at taking actions to minimise the endogenous fire hazard (Krause & Smoliński, 2013; Trenczek, 2008; Tutak & Brodny, 2017). The actions currently taken in mines include continuous monitoring of the concentration of gases in the mine air (carbon oxide, hydrogen and unsaturated hydrocarbons: ethylene, propylene and acetylene), which are emitted into mine air as the temperature of self-heating coal increases. Presence of the gases in

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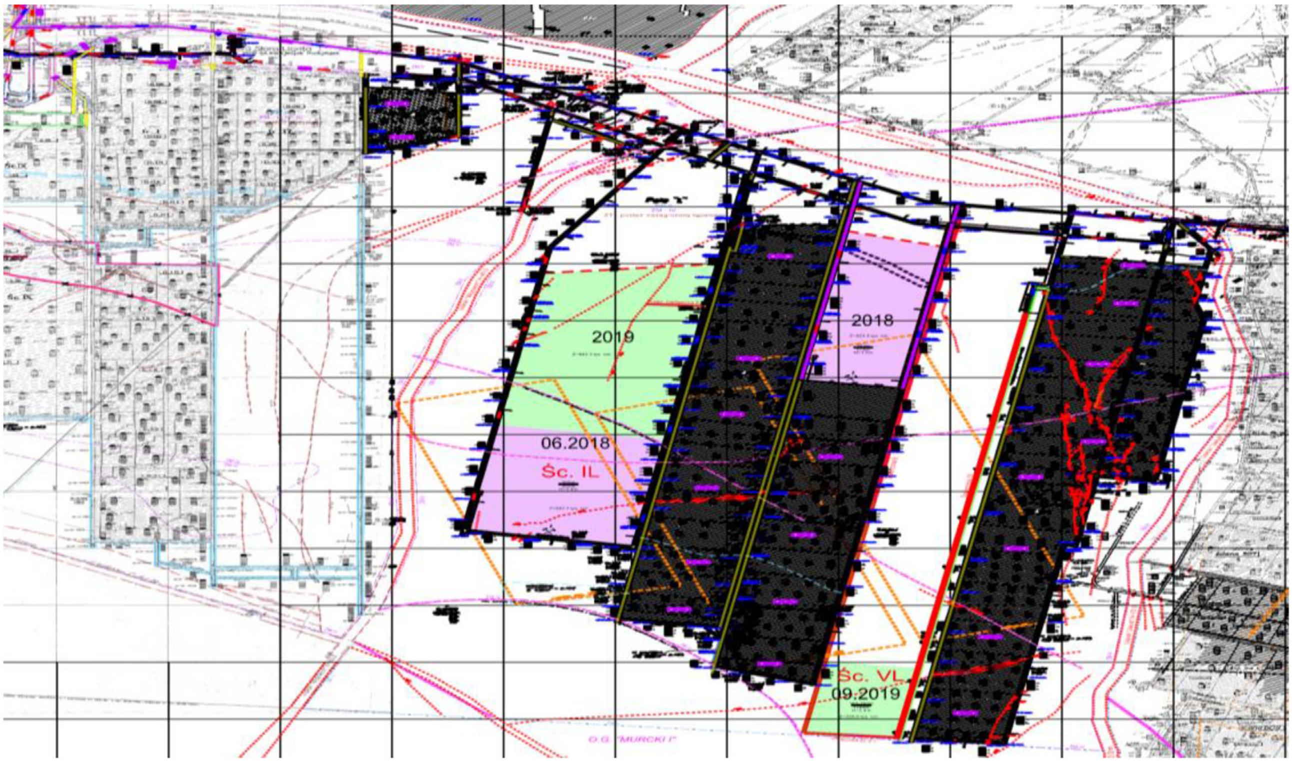

Fig. 1. Map of mine workings in hard coal mine with extended rock mass monitoring with temperature sensors.

the mine air and measurements of their concentration help determine so-called fire indicators (Liang, Zhang, Wang, Luo, & Ren, 2019; Liu, Qin, Yang, Wang, & Chen, 2018; Wojtacha-Rychter & Smoliński, 2018a; Wojtacha-Rychter & Smoliński, 2018b,c, 2019). Basing on them, it is possible to forecast the temperature of a self-heating deposit. It is a method commonly used in Polish hard coal mines. Proper assessment of the stage of self-heating enables taking right actions aimed at eliminating foci of self-heating, which prevents occurrence of an endogenous fire. One of the disadvantages of the method of continuous air monitoring in the areas of endogenous fire hazard (besides the obvious financial aspect because continuous monitoring generates costs) is associated with the aspects of the nature of coal itself. Hard coal, due to its porous structure is capable of absorbing vapours and gases. Gases desorbed from the focus of coal self-heating (located within solid coal) such as ethylene, propylene and acetylene, may be sorbed while migrating through goafs, which lowers concentration of the gases in the mine air and may distort the values of fire indicators calculated on their basis. In turn, it may lead to false conclusions during endogenous fire hazard assessment. When coal self-heating is detected in a mine, preventive actions are taken: injecting minerals and inert gases into sidewalls of raises along goafs and caved roof area; irrigating sidewalls of mine workings, cooling goafs with fly ash with frequency adjusted to the absorbency of goafs, maintaining mobile probes aiming caved longwall to collect air samples every 30 powered roof supports, measuring the temperature of sidewalls and the roof with a thermal imaging camera, maintaining ducts for nitrogen inertization with CNLP 1500 in all the mine workings.

Due to complex causes of endogenous fire occurrence (natural, mining and technical), preventing fires depends on the scope and method of monitoring and early start of preventive measures.

The aim of the article is developing and testing a new system, based on temperature measurements in solid coal for predicting coal self-heating hazard, in an operating mine. The system is not an alternative to the existing methods. It ought to be rather treated as a supplement to the methods currently applied in mining industry which are based on measurements of gases emitted during the process of coal self-heating. The proposed system, based on measurements of temperature in solid coal with a system of temperature sensors within solid coal in all the driven mine workings, was tested in the working conditions of an operating hard coal mine located in w the Upper Silesian Coal Basin (USCB, Poland).

2. Materials and methods

The developed method, employing a system of temperature sensors placed within the solid coal in all the driven mine workings, was tested in an operating hard coal mine.

3. Materials

The newly-developed system of monitoring solid coal temperature was tested in seam 405 panel L of mining area (O.G.) Giszowiec I, level 680 m, which has been exploited since 2012, in operating Wujek mine located in the USCB (Poland).

Seam 405, panel L of O.G. Giszowiec I, is deposited between approximately 700 m (−410.0 m a.s.l.) in the north, and approximately 800 m (−505.0 m a.s.l.) in the south, with average southbound and south-western bound inclination of approximately 3–8°.

The thickness of seam 405 in panel L is between 2.9 and 4.0 m. Within the seam there are between approximately 0.05- and approximately 0.2-m-thick layers of clayey shale or coal shale. In the southern part of the panel to be mined, the intercalation occurring in the seam increases to approximately 1.3 m splitting seam 405 into two benches, an upper one of the approximate thickness of 1.0–1.85 m and a lower one of the approximate thickness of 2.0–2.6 m.

Faults mark three borders of panel L. They are: in the north, Kłodnica fault of approx. 100–120 m down-to-the-south throw; in the west, Wojciech fault of approx. 33–60-m down-to-the-east throw; and, in the east, Jakub fault of approx. 40–70-m down-to-the-west throw. In the south, the panel is limited by the border of mining area Giszowiec I. South of the border is located Środkowy fault of 20–25-m down-to-the-south-west throw.

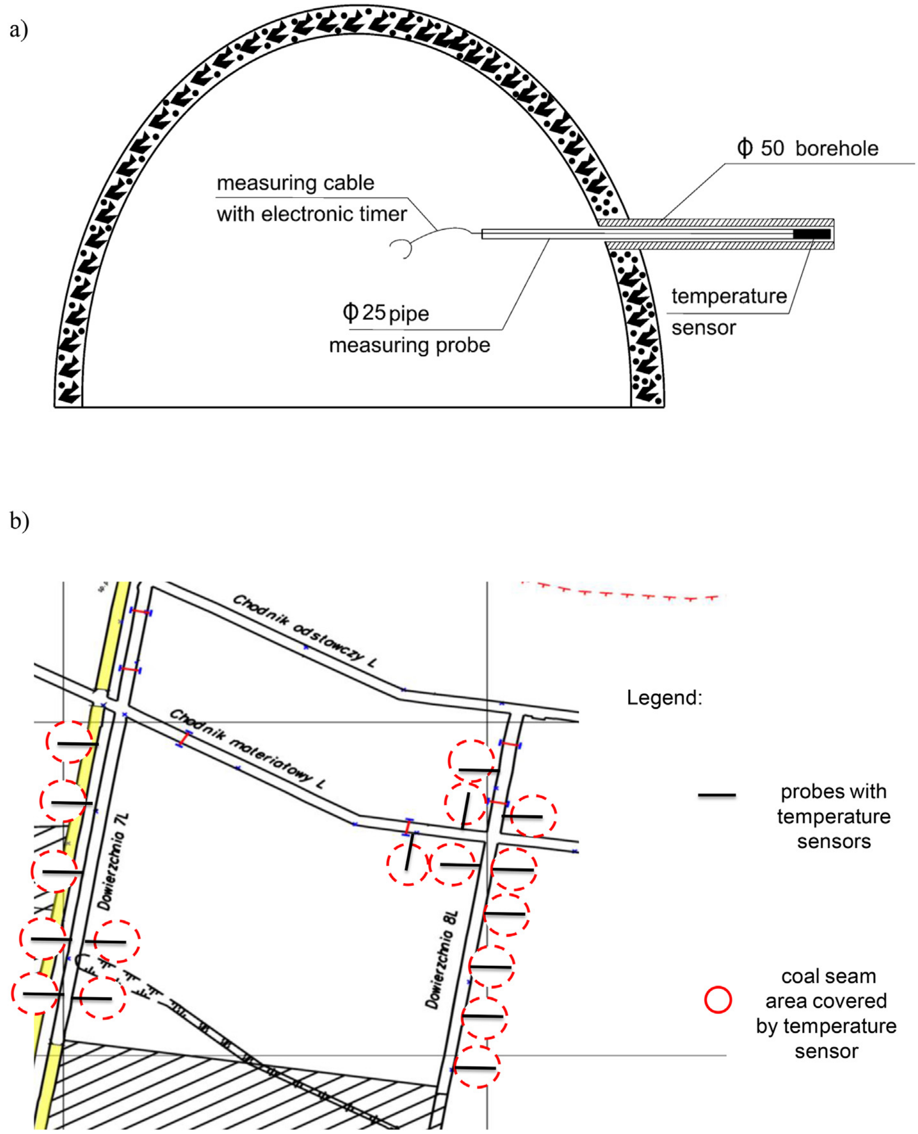

Fig. 2. a) Schematics of probe with temperature sensor installed in mine workings, b) schematics of probe distribution.

Within the seam, there has been already discovered a NE-SW fault of 12.7-m down-to-the-north-west throw. Moreover, there is also a roughly W-E fault of 1.2 m down-to-the-south throw.

The lithological profile of the rocks in the roof is presented in the profile of the boreholes: Gp-1/13 (penetrometric), H-6/13 and H-7/13. The lithological profile of the rocks in the floor of the seam was determined basing on borehole G-1/13.

The immediate roof of seam 405, basing on the boreholes made when development workings were driven, is formed of a 0.8–6.0-m-thick layer of clayey shale with a layer of either sandstone or sandy shale above.

The immediate floor of seam 405 is made of a layer of clayey shale. The stone – coal and coal workings, which were driven to open up seam 405, panel L of O.G. Giszowiec I, crossed a number of faults and ran in the vicinity of goafs remaining after prior coal mining works.

4. Methods

To expand significantly fire prevention monitoring in the mine, there were used temperature sensors placed within solid coal in all the driven mine workings. Basing on the model of coal self-ignition, the following temperatures were determined:

T_1 – 40 °C danger point,
T_2 – 60 °C critical point,
T_3 – 80 °C turning point,
T_4 – 180 °C pyrolysis point,
T_5 – 300 °C self-ignition point (minimal fire temperature).

A new system of predicting coal self-heating was developed basing on a system of temperature sensors placed within solid coal in all driven coal and stone workings where they cross coal seams. Fig. 1 shows the map of mine workings where extended rock mass monitoring with temperature sensors was implemented.

Temperature sensors together with measuring probes were placed in mine workings, intersections, geological disturbances (faults), chain pillars, caved longwalls and other appointed places (see Fig. 2).

Systematic temperature monitoring in solid coal was accompanied with continuous monitoring of gases in the mine air and observation of sidewall and roof surfaces with thermal imaging cameras.

Sensors, type KTY 81–210, were applied to measure the temperature in a mine. The sensors did not have own source of power and were powered by Nova's temperature measuring device TC 125. The distance of the sensor from the device depends on the total resistance of the probe connection cable and the level of disturbances which may be

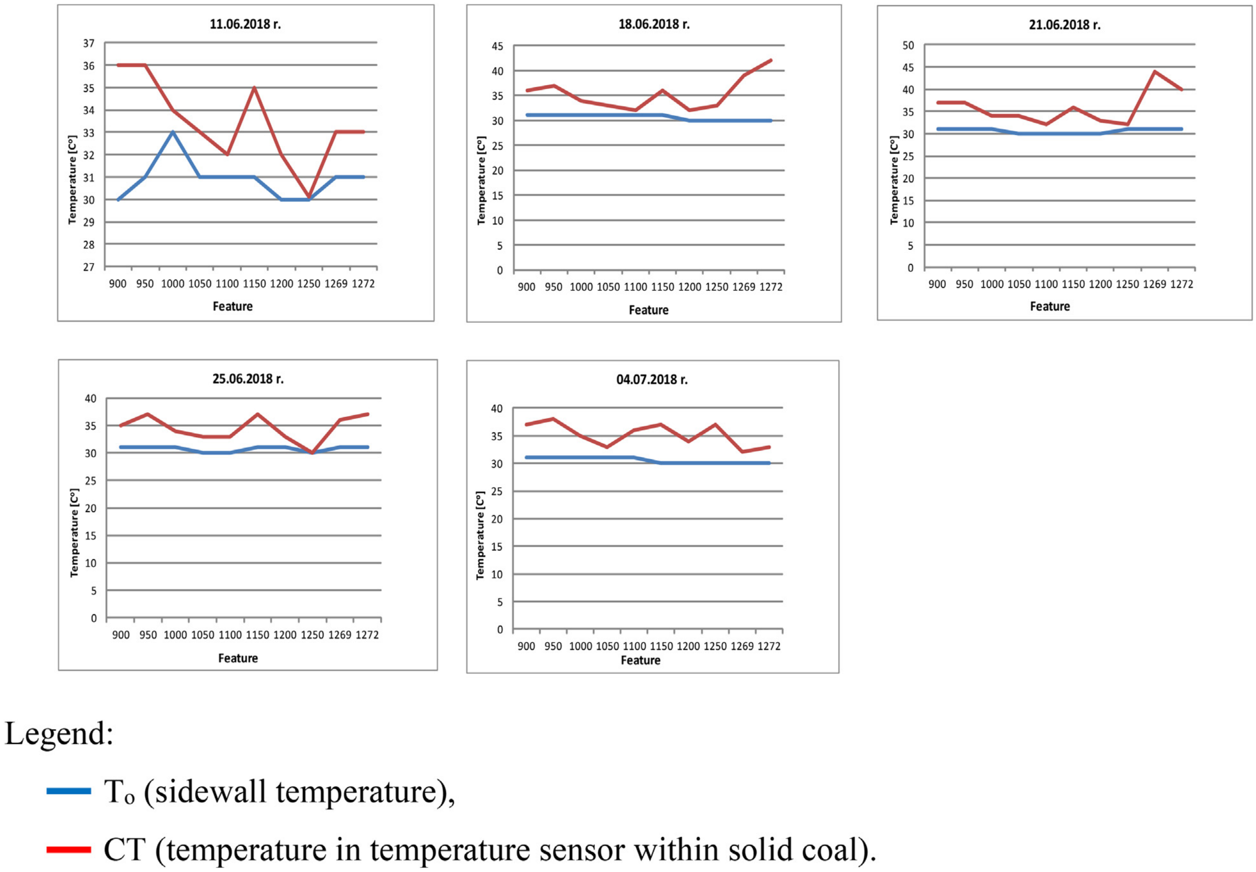

Fig. 3. Temperature of solid coal, example 1.

generated in the long section of a wire.

Fire hazard monitoring is conducted through checking probes with installed measuring sensors by appointed personnel – certified ventilation inspectors. Using portable equipment they check both the measurements of the temperature sensors within the rock mass and gases in the probes. At the same time, the temperature of sidewalls and the roof is measured with a thermal imaging camera. The temperature and the change in gas emission from the probes are immediately compared with the results of previous measurements. There are also collected samples of gases for chemical analyses. Additionally, the thermal imaging camera recordings are analysed.

Basing on own observations in Wujek mine, due to an increase in the concentration of mine operations and, first of all, common use of diesel-powered vehicles, the method of early detection of endogenous fire, developed by GIG, as well as monitoring mine workings with thermal imaging cameras turned out to be insufficient to detect endogenous fire, especially at its initial stage.

Gas analyses of air samples are often disturbed by gas emissions from diesel-powered equipment or welding works. The emission of gases itself, indicating an advanced stage of coal self-heating, is just an element confirming either high intensity of the self-heating process or direct fire hazard.

An elevated level of ethylene, propylene, acetylene, carbon oxide and hydrogen in air samples means that somewhere within the rock mass, in solid coal, there is already intensively developing an endogenous fire or, at least, the critical temperature of coal self-heating is exceeded, which is, according to research, approximately 60°.

The technical and mining conditions forced the mine to take new activities, going beyond the currently-binding regulations, while monitoring an endogenous fire.

5. Results and discussion

Until 2012, the mine exploited coal seams 504, 510, 404/5 and 405 in two mining levels. As the deposits in the seams depleted and the mining works advanced, they focused on newly accessed panel L of seam 405, level 680 m. The mine was based upon a model with one operating longwall and two or three faces preparing another longwall. The concentration of mining works in one area, seam 405 panel L of O.G. Giszowiec I, was associated with maintaining continuity of works. Any technical problems or hazards meant ceasing production and financial losses which may lead to the mine closure and in turn the personnel redundancies. The actions taken and the technical solutions applied in the mine were aimed at minimising potential losses. Fire was considered to be the most serious hazard in the area as, if it occurred, it could render all mining operations impossible. Hence the coal seam was additionally monitored with temperature sensors.

Due to the fact that there are no publications concerning methods of monitoring the temperature of coal seams with temperature sensors in an operating mining enterprise, it was necessary to specify precisely the aim of applying such sensors, their distribution and interpretation of the obtained results.

Basing on the general knowledge of underground fires, it was assumed that the main objective is as precise as it is only possible determination of the place in mine workings, where endogenous fire is developing. It was necessary to apply temperature sensors which were distributed in such a way that two neighbouring temperature sensors covered the area where the temperature increased significantly as a consequence of the development of an endogenous fire.

Introducing so-called 'actual seam temperature', after installing a temperature sensor, also required posing a question if, knowing that the rock mass temperature – coal is increasing, it automatically means serious fire hazard and if it is possible to observe further increase in the

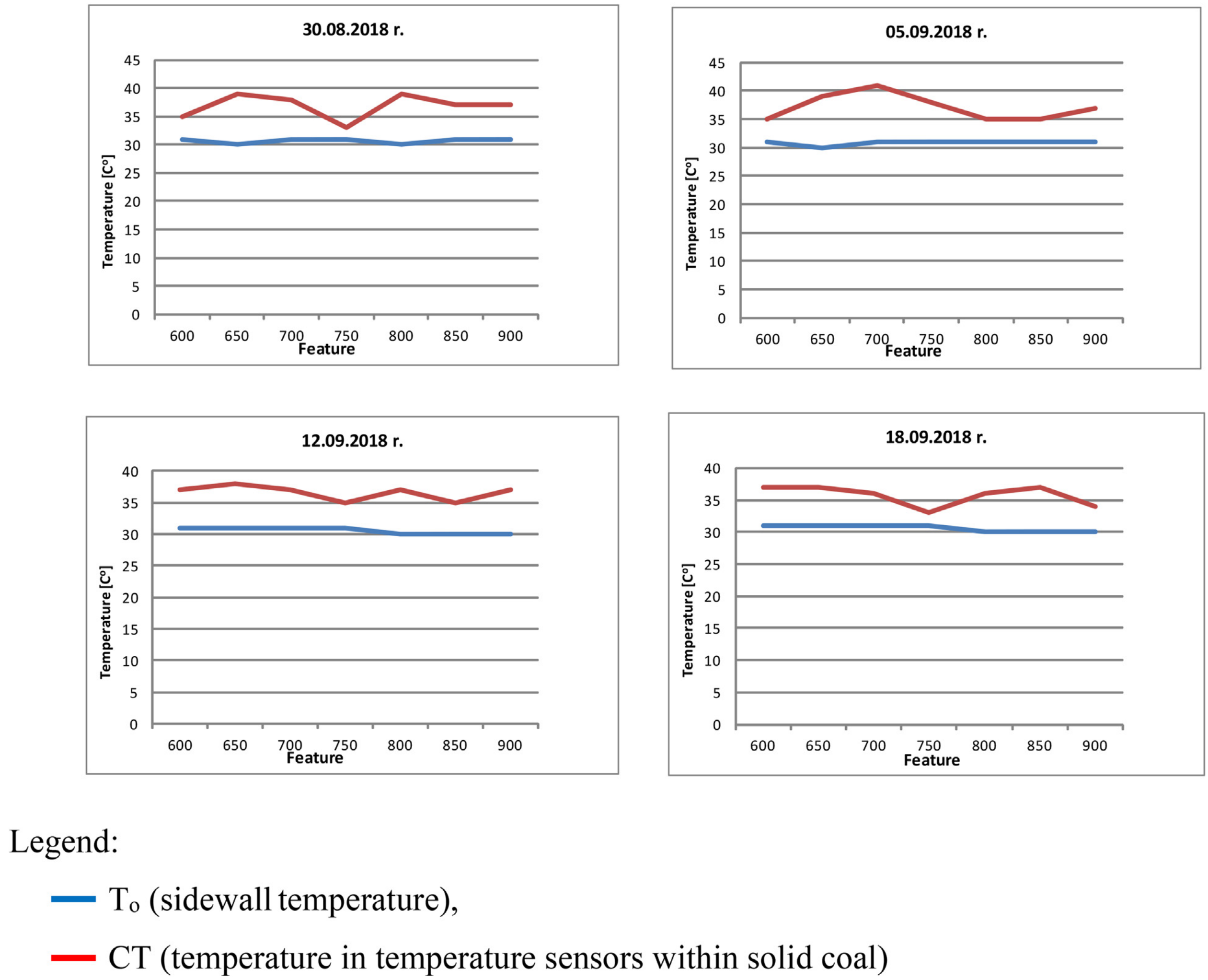

Fig. 4. Temperature of solid coal, example 2.

temperature without taking any preventive actions.

In an active mine, it turned out that seam 405 L, seemingly a seam undisturbed with mining activities, was actually either cracked or subjected to the influence of mining operations in nearby seams or panels.

The consequence of the natural disturbances, i.e. faults, undulating and seam intercalations, is the fact that an endogenous fire may be expected to develop in virtually any place of the seam accessed with new mine workings.

Taking into consideration the actual natural conditions means that 'monitoring' has to predict development of an endogenous fire in any place of the seam. Additionally, it has to consider the influence of changes in the aerodynamic potential between seams, levels, goafs and mine workings in an exploited seam, i.e. assess what information we receive when we measure the temperature.

Monitoring temperature in a coal seam with temperature sensors, in most cases precedes basic criteria of the fire hazard assessment by collecting air samples. It is possible to determine an increase in coal temperature i.e. the development of an endogenous fire in the areas of intersections, chain pillars and mine workings surrounded by goafs, with faults subjected to the pressure drop of the main fans, i.e. in places where the emitted gases are "drawn" to other places in the mine or get accumulated in goafs, until the fire manifests itself and develops so violently that there is a sudden outflow of fire gases into mine workings.

Continuous monitoring of a coal seam with temperature sensors can be treated as a way of discovering a fire before it manages to develop. The sensors were also included into the CO monitoring and measuring system.

As the solution turned out to be useful in monitoring temperature of a coal seam, the next stage of the development of the method of endogenous fire monitoring may be connecting all the temperature sensors installed in the rock mass into an electronically monitored network. Each mining enterprise producing coal is obliged to follow safety procedures imposed by the geological and mining regulations and the regulations for underground mining enterprises. Due to the personnel's safety, in an operating mining enterprise, it is impossible to conduct any kind of research which would mean exceeding the standards imposed by the regulations.

For the needs of coal seam monitoring with temperature sensors, the assumptions concerning the development of an endogenous fire, coal temperature and emission of fire gases are based on the current knowledge of the phenomena.

The distribution of temperature sensors and interpretation of the results of the temperature measurements, made at given time intervals, assumed that confirmed systematic increase in coal temperature, has to trigger certain fire prevention activities which the regulations oblige a mining enterprise to conduct.

An analysis of a few thousand measuring points in seam 405 conducted over a few years enabled experimental determination of the safety threshold, i.e. the temperature of coal of approximately 42–44 °C, which, when exceeded, has to trigger fire prevention activities in a given place. For different coal seams, the danger temperature differs,

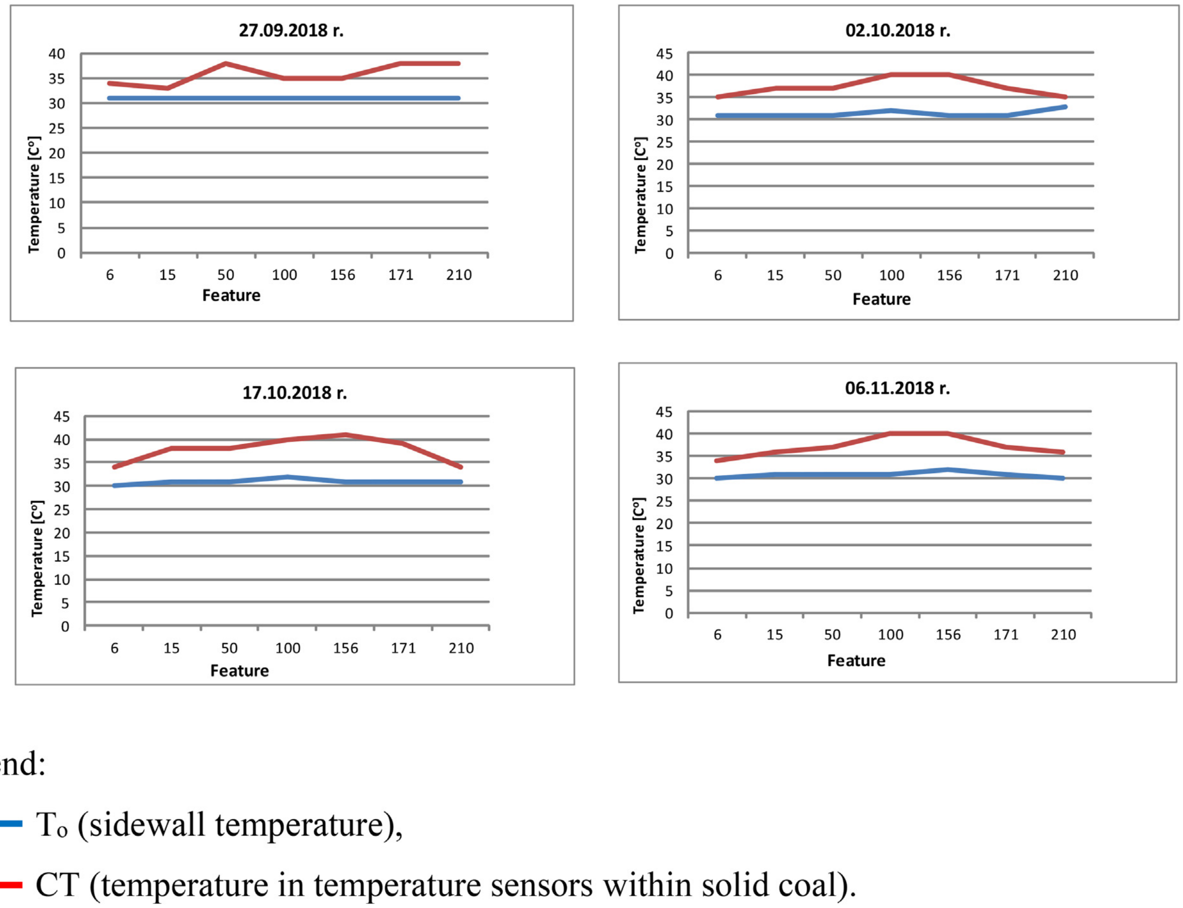

Fig. 5. Temperature of solid coal, example 3.

Table 1
Lithological profile of layers in given boreholes.

Seam roof boreholes		
Gp-1/13	H-6/13	H-7/13
1.5 m clayey shale	0.8 m clayey shale	6.0 m clayey shal
2.2 m sandy shale	4.2 m sandstone	4.0 m sandstone
0.2 m clayey shale	0.3 m coal	
0.6 m sandy shale	6.4 m clayey shale	
3.7 m clayey shale sandstone		
• Seam floor borehole		
• G-1/2013		
• 12.75 m clayey shale		

e.g. for seam 510 in Wujek mine, it is the coal temperature of about 40 °C.

Following such an assumption, there were taken preventive actions such as injecting water, nitrogen, minerals; or stopping further development of an endogenous fire. Prevention activities are often limited by the mining and technical capabilities of a mine. Nevertheless, at the initial stage of development of an endogenous fire, it is possible to stop it.

In the analysed period, between January 1 and December 31, 2018, due to wide application of fire prevention activities after observing an increase in the temperature over 40 °C, there were only a few examples of either an increase in the temperature above the danger temperature, or observed emissions of an increased amount of fire gases. Moreover, they were only observed in the measuring probes. Gases emitted from self-heating coal did not flow into mine workings yet.

Observing an increase in the temperature, much over 42 °C, with the temperature sensors, meant it was necessary to show that, in an active mine, observations of coal temperature provide information about the development of an endogenous fire before the knowledge is obtained only by analysing air samples.

The figures (see Figs. 1–3) present three examples where, basing on current measurements of temperature, there was observed a local increase in the temperature within solid coal. Local increase in temperature was neither sudden nor sharp, however it was noticeable in relation to other places (see Fig. 5) (see Fig. 4).

In each of the cases, it is necessary to mention, that, initially, in the measuring probes, there was not observed any increase in the concentration of gases which could clearly indicate the development of coal self-heating (see Tables 1–3). Gases emitted from coal self-heating appeared only in the measuring probes. They were not observed in the air current. It means it is possible to determine accurately the area of self-heating before coal self-heating gases appear in the mine air (see Table 4).

The presented examples are representative for all points (measuring probes).

The given examples of measurements with probes in mine workings and the graphs clearly illustrate changes in the rock mass temperature over the analysed period of time. We observed a significant increase in the rock mass temperature over 40 °C for the presented examples. For the needs of the tests, the time of observing an increase in temperature was "outwaited", without taking any preventive measures. However, reaching the temperature over 40 °C by a sensor within solid coal was in each case considered to be the end of the safe fire development. The preventive actions were taken and the coal temperature stabilised.

Air samples were collected from the probes installed near temperature sensors for chemical analyses with the GIG method.

Table 2
Concentration of gases in probes, example 1.

11.06.2018						
Feature	CO	CO_2	CH_4	O_2	T_o	CT
	ppm	%	%	%	°C	
900	20	1.4	5	15.1	30	36
950	40	1.3	2.1	19.1	31	36
1000	70	1.4	5	9.1	33	34
1050	40	1.4	2.8	15.0	31	33
1100	IRRIGATION				31	32
1150	60	1.4	2.2	10.8	31	35
1200	7.2	1.2	5	15	30	32
1250	50	1.4	3.2	14.0	30	30.1
1269	182	1.2	4.0	12.0	31	33
1272	180	1.4	5.0	15.0	31	33
18.06.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
900	48	0.8	1.4	17.2	31	36
950	50	0.3	0.3	18	31	37
1000	69	2	5	7.1	31	34
1050	18	0.3	0.2	20.0	31	33
1100	30	0.4	1.6	17.4	31	32
1150	10	0.2	0.1	20.0	31	36
1200	IRRIGATION				30	32
1250	48	0.1	0.7	17.8	30	33
1269	400	3.2	12.0	10.0	30	39
1272	410	2.8	10.0	11.2	30	42
21.06.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
900	36	3.8	0.7	5.9	31	37
950	17	0	0.4	1.1	31	37
1000	40	1.6	7.2	8.4	31	34
1050	40	0.2	1.4	18.8	30	34
1100	30	1.4	1.6	17	30	32
1150	60	1.2	1.9	11.0	30	36
1200	30	4.4	1	7.2	30	33
1250	94	2.6	5.0	6.7	31	32
1269	475	3.8	11.2	9.6	31	44
1272	480	3.2	10.0	11.0	31	40
25.06.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
900	30	0.4	0.7	18.9	31	35
950	0	0.2	0.3	6.6	31	37
1000	40	2.4	40	11.6	31	34
1050	10	0.7	1.3	16.4	30	33
1100	20	0,5	0,9	19,8	30	33
1150	40	0.8	1.6	17.4	31	37
1200	20	0.6	1.2	17.8	31	33
1250	60	1.6	3.6	8.4	30	30
1269	IRRIGATION + INERTING N_2				31	36
1272					31	37
21.06.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
900	40	1.9	2.8	19.3	31	37
950	75	1.8	1.3	4.6	31	38
1000	30	2.4	28	6.1	31	35
1050	10	0.7	1.3	16.4	31	33
1100	0	1.4	1.7	16.4	31	36
1150	50	1.4	2.4	17.4	30	37
1200	30	1.9	6.6	16.3	30	34
1250	70	2.3	7.4	10.2	30	37
1269	IRRIGATION + INERTING N_2				30	32
1272					30	33

Table 3
Concentration of gases in probes, example 2.

30.08.2018						
Feature	CO	CO_2	CH_4	O_2	T_o	CT
	ppm	%	%	%	°C	
600	80	2.2	64.0	0.6	31	35
650	20	1.4	1.0	7.8	30	39
700	0	2.6	7.0	6.2	31	38
750	0	0.1	3.6	17.4	31	33
800	0	0.6	1.2	18.4	30	39
850	0	2.8	1.4	15.4	31	37
900	50	1.2	0.8	7.4	31	37
05.09.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
600	160	1.0	1.3	11.6	31	35
650	30	1.0	0.8	6.2	30	39
700	10	1.0	14.0	6.2	31	41
750	0	0.6	1.1	19.0	31	38
800	10	1.4	1.7	19.6	31	35
850	20	1.0	1.6	18.4	31	35
900	120	0.3	1.6	12.4	31	37
12.09.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
600	160	1.0	1.3	11.6	31	37
650	IRRIGATION + INERTING N_2				31	38
700					31	37
750	0	0.6	1.1	19.0	31	35
800	10	1.4	1.7	19.6	30	37
850	20	1.0	1.6	18.4	30	35
900	120	0.3	1.6	12.4	30	37
18.09.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
600	170	1.3	1.1	15.6	31	37
650	40	1.8	3.0	5.1	31	37
700	20	1.7	3.1	5.8	31	36
750	0	0.4	1.7	19.6	31	33
800	10	1.4	1.7	19.6	30	36
850	280	0.2	1.4	14.1	30	37
900	40	0.6	3.6	17.2	30	34

The samples contained fire gases, i.e. ethylene, propylene, acetylene and hydrogen of values exceeding the threshold marking the development of an endogenous fire. It has to be emphasised that there were no signs of a fire developing in the mine workings. The applied preventive measures completely stopped further development of fire hazard.

6. Conclusions

1. In the mining and geological conditions, there were observed fluctuations in temperature over time. An increase in the temperature often occurred before there was observed any increased emission of gases in solid coal. The temperature within the rock mass was significantly higher than its surface, and the increase in the temperature of the sidewall surface occurred much later than within the cracked rock mass. Taking immediate preventive actions, (irrigating, sealing sidewalls with minerals, supplying inert gases, cooling goafs with fly ash) resulted in a drop in the temperature within the rock mass and return to the normal state.
2. Basing on the model of coal self-heating, in the geological and mining conditions of a mine, an increase in the temperature within the rock mass to approximately 40 °C, i.e. the danger point, is the

Table 4
Concentration of gases in probes for example 3.

Feature	CO	CO_2	CH_4	O_2	T_o	CT
27.09.2018						
	ppm	%	%	%	°C	
6	120	0.7	1.9	18.6	31	34
15	245	2.4	5.0	2.1	31	33
50	230	0.3	2.4	15.6	31	38
100	220	2.3	5.0	12.6	31	35
156	240	2.3	5.0	12.6	31	35
171	200	3.1	4.8	8.8	31	38
210	235	2.8	5.0	15.2	31	38
02.10.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
6	110	0.9	2.0	17.6	31	35
15	220	2.2	6.7	6.0	31	37
50	180	0.8	1.6	16.0	31	37
100	200	1.8	5.0	13.6	32	40
156	210	2.2	7.2	6.0	31	40
171	140	1.4	2.8	15.0	31	37
210	220	3.2	6.2	6.0	33	35
17.10.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
6	140	1.3	2.4	19.6	30	34
15	110	3.4	5.0	10.3	31	38
50	190	0.5	3.1	16.3	31	38
100	170	1.3	4.9	14.1	32	40
156	IRRIGATION + INERTING N_2				31	41
171					31	39
210					31	34
06.11.2018						
Feature	**CO**	**CO_2**	**CH_4**	**O_2**	**T_o**	**CT**
	ppm	**%**	**%**	**%**	**°C**	
6	180	1.6	5.0	11.6	30	34
15	140	1.4	3.8	9.6	31	36
50	IRRIGATION + INERTING N_2				31	37
100					31	40
156					32	40
171	40	1.0	1.7	9.6	31	37
210	30	3.4	2.6	6.2	30	36

threshold above which the temperature rapidly increases over short time and simultaneous emission of gases, especially CO and CO_2.

3. As a result of the conducted tests, there was observed emission of fire gases from the solid coal at the temperature over 50 °C.
4. It was concluded that the increase in temperature to 40°–50 °C within solid coal causes virtually no changes in the temperature on the surface of sidewalls.
5. Much earlier detection of the places of coal self-heating, before gases, emitted as a result of coal oxidation and fire, appear in the mine air, enables complete elimination of coal self-heating in a given place.
6. When the rock mass temperature was monitored with sensors located within solid coal, no increase in the concentration of fire gases was observed in the currents of the mine air. By applying such a monitoring system and then taking immediate preventive actions, it was possible to prevent endogenous fire hazard from developing.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jsm.2019.04.002.

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