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SOME ASPECTS OF SAFE DE-STIMULATION OF SELF HEATING OF COAL

NĚKTERÉ ASPEKTY BEZPEČNOSTI DEAKTIVACE RIZIKA SAMOVZNÍCENÍ UHLÍ

Abstract

The paper presents a multi-componential set of both internal and external stimulants that contribute to the process of coal self-heating. Special attentions is paid to the importance of detailed analysis and examination of existing levels of stimulants for the purpose of adequate addressing of fire-protecting measures to achieve efficient de-stimulation. Among preventive actions against endogenous fires the prophylactic and de stimulating measures are extremely essential, where prophylactics is understood as optimization of componential factors on the stage of design and development of mining operations whilst de stimulation means counteracting against activity of stimulants. Therefore importance of thorough analysis of the existing fire stimulants must be discussed in order to find out the most efficient de stimulating measures. Selected characteristics of inert gases and water are presented with special regard to adverse and hazardous side effects that may occur under specific circumstances. Finally, comparison of beneficial and adverse effects is made for the cases when inert gases and /or water are applied.

Abstrakt

Článek uvádí víceparametrovou kompilaci vnějších a vnitřních ovlivňujících faktorů spjatých s procesem samovznícení uhlí. Zvláštní pozornost je věnována významu detailní analýzy aktivačních faktorů požárního rizika se záměrem docílení deaktivace daného procesu. Je zde podána charakteristika vybraných vlastností inertních plynů a vody na základě anylýzy jejich negativních vědlejších účinků, které se projevují za daných podmínek při jejich aplikaci. Závěrem jsou předloženy poznatky z oblasti porovnání předmětných vedlějších účinků při použití voda a inetrtních plynů pro dané účely.

Key words: hard coal – mining – mining aerology – breeding fire – de-stimulation fire hazards.

1 INTRODUCTION

Hard coal, being a common fossil fuel, is a valuable raw material for power generation. In Poland the fuel in mined from underground collieries with large number of associated hazards. Endogenous fires represent one of such risk factors where the degree of danger depends on many aspects. These aspects affect in more or less stimulating manner onto the process of coal self-heating, therefore they can be defined as stimulants and roughly subdivided into internal and external ones [6,9] (Table 1).

The above breakdown shows that humans to no extent can affect internal stimulants as well as natural stimulants classified as external ones. However other stimulants remain under human's control but the degree of controllability is quite variable.

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Table 1. Set of basic factors that stimulate the coal self-heating process

Internal stimulants	Direct	Natural susceptibility of coal to self-ignition;
		Activation energy for coal oxidation;
		Moisture content of coal;
	Indirect	Primary temperature of coal;
External stimulants	Natural	Internal pressure of cracking degree of coal beds;
		Occurrence of quakes;
		Thickness of coal beds;
		Inclination of coal beds;
		Depth of excavations;
	Mining-related	Mining system;
		Direction of excavation advance;
		Longwall length;
		Thickness of coal layer that is left in goafs;
	Technical and organizational	Completeness of excavation;
		Directed isolation of goafs aimed at methane prevention;
		Air velocity or intensity of ventilation;
		Longwall advance per month;
		Start-up period of longwalls;
		Method (system) of ventilation;
		Air temperature at longwalls;
		Time period of longwall dismantling;
		Active bump-protecting prophylactic measures;

2 IMPORTANCE OF DE STIMULATION WITH REGARD TO LEVEL OF HAZARDS

All the internal stimulants define primarily how much the specific coal is vulnerable to self-heating. Such a process can merely occur if a specific energetic barrier is overcome, whereas the barrier is defined as the energy of coal oxidation *A*. It means that some particles of oxygen must acquire a specific minimum dose of energy (energy of activation) in order to initiate the process of chemical sorption of oxygen by coal and low-temperature oxidation of coal [13].

In accordance with the relevant standard that is in force in Poland, every coal bed is classified in terms of its vulnerability to self-heating and assigned to one of five groups. In spite of the activation energy, the laboratory-determined self-heating factor is regarded as the parameter that decides about classification into one of the above groups. The safest coal beds are associated with the 1st group whereas the most hazardous – with the 5th one in terms the coal self-ignition susceptibility.

However the potential self-heating of underground coal beds predominantly depends on external factors, that thesis is confirmed by relatively frequent cases of endogenous fires in beds where the coal had not been classified into the highest groups of self-ignition hazards [7] (Table 2).

Table 2. Endogenous fires in Poland over the years 1996 – 2005 vs. classification to the group of coal self-ignition hazards

Group of coal self-ignition hazards	Number of fires per year										Total	%
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005		
I	1	-	-	-	-	-	-	-	1	-	2	5
II	1	3	4	1	1	-	1	1	2	4	18	43
III	2	-	-	-	-	1	-	1	-	2	6	14
IV	2	-	1	1	1	-	1	1	1	-	8	19
V	1	1	-	1	-	-	2	1	1	1	8	19
Altogether	7	4	5	3	2	1	4	4	5	7	42	100

Optimization of the procedures dedicated to design and development of mining operations plays crucial role in limitation of the probability of the fact that the process of coal oxidation may advance from its initial stage to the self-heating level (Fig. 1) [4]. The optimization procedures are aimed at cost effectiveness of the mining operations with assurance of work safety, including minimization of hazards of endogenous fires.

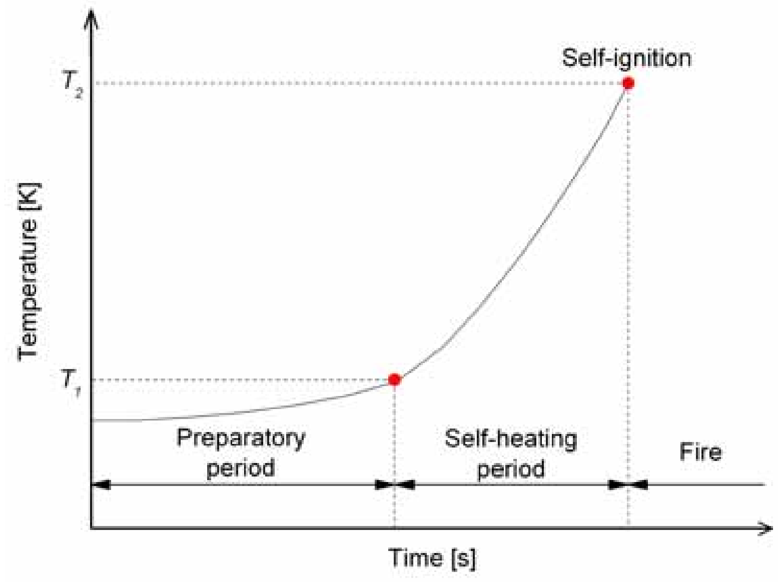

Fig. 1. Coal self-ignitability model.

Therefore fire prevention and other prophylactic actions consist in selection of the most appropriate method of coal mining, roof development, ventilation system, longwall length, monthly advance and choice of the most adequate longwall equipment that best suit the actual circumstances. These are the factors that inhibit the coal oxidation process. However, in predominant number of cases such a prophylactics is infeasible and cannot be applied in the full scope due to the existing circumstance, hence is hardly effective. It is why the process of coal self-heating may occur.

During the period of coal self-heating the main stress of fighting against endogenous fire hazards is put to de-stimulating operations, i.e. the measures that counteract against activity of fire stimulants. Owing to permanent progress in techniques and technologies employed for such operation endogenous fires occur really hard, in major cases in the region of roof-fall longwalls [7] (Table 3).

Table 3. Breakdown of endogenous fires in Poland over the years 1996-2005 by the regions of their origin

Region of origin	Number of fires per year										Total	%
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005		
Within regions of roof-fall longwalls	2	2	3	-	1	1	2	4	5	7	27	64
Within regions of longwalls with full filling of cavities	1	1	1	-	-	-	-	-	-	-	3	7
Outside regions of coal excavation	4	1	1	3	1	-	2	-	-	-	12	29
Altogether	7	4	5	3	2	1	4	4	5	7	42	100

Endogenous fires occur the most frequently when circumstances, i.e. external stimulants, are so conducive to dynamic development of the coal self-heating process that the applied de-stimulating measures, even the most effective, is unable to keep pace with the dynamics of stimulating factors. As it is generally assumed that one endogenous fire occurs for about 10 - 15 cases of fire hazards when de-stimulating measures must be commenced [10]. Thus, the de-stimulation cannot be overestimated, in particular in current economic situation in coal mines, where business related reasons enforce reduction of the number of operated longwalls with simultaneous growth of average daily coal production of a single longwall (Table 4). Thus, all the direct or indirect costs related to potential fires and loss of production can reach extremely high levels.

Table 4. Balance of coal production against number of operated longwalls and endogenous fires in the region of longwalls over the years 1996-2005

No	Year	Coal production [m. tons]	Total number of longwalls	Longwall types				Number of endogenous fires
				with roof fall	%	with filling of cavities	%	
1	1996	136	363	278	77	85	23	3
2	1997	137	305	244	80	61	20	3
3	1998	116	263	218	83	45	17	4
4	1999	109	234	203	87	31	13	-
5	2000	102	183	167	91	16	9	1
6	2001	102	161	149	93	12	7	1
7	2002	102	151	142	94	9	6	2
8	2003	100	150	142	95	8	5	4
9	2004	99	135	127	94	8	6	5
10	2005	97	133	125	94	8	6	7

3 TRENDS IN DE-STIMULATION OF THE COAL SELF-HEATING PROCESS

When de-stimulating operations are planned and scheduled, it necessary to recognize all the stimulants that are associated with the specific coal excavation process. It is mandatory, as it may even happen that some of undertaken measures are improperly oriented – they are addressed to a factor that is not an actual stimulant. Such measures are obviously senseless and bring no positive effect.

De-stimulation of external factors may depend on a number of components, which is reflected in various level of possible effective counteracting the possible hazards. Hazard of endogenous fire can firstly occur in the region of the operated longwall when unmined coal is left in goafs. It is why thickness of coal layer that remains in goafs and its coarse /fine fraction rate is the matter of crucial importance.

If other circumstances have led to the coal self-heating process, de-stimulation of that process may be carried out either by alteration of some technical and organizational parameters of the mining operations (e.g. mitigation of air migration into goafs, increase of daily advance of the longwall) or apply an additional de-stimulating component (e.g. cyclical spraying of goafs with water, flushing of goafs with filling material /mud, inertization of goafs). The above measures can be applied jointly at the same time.

Inertization represents the method that is quite frequently used for a de-stimulation of the self-heating process [1,2,3,5,8,11] due to the high efficiency of that approach. However, it is the method that has its advantages and disadvantages, similarly to any other components of a de-stimulation process of the self-heating policy. All that strong and weak sides should be taken into the consideration.

4 SELECTED PROPERTIES OF NITROGEN< CARBON DIOXIDE AND WATER

Use of water or inert gases to prevent self-ignition of coal takes advantage of specufuc properties of such materials that de-stimulate (mitigate) the coal self-heating process. The mitigating effect can result from direct contact of the agent with the location under the danger of self-heating or from indirect impacts that are aimed at activation of other factors that de-stimulate (mitigate) the hazards [6].

In case of water, effectiveness of the de-stimulation results from its inflammability. It makes possible to flood the locations of coal self-heating and disable ingress of oxygen into the hazardous area. Consequently, the self-heating process in stopped and the location starts to cool down. Yet it must be stressed that application of water (from a fire-fighting or a filling pipeline) as a preventing measure in case of endogenous fires leads to the best and the most satisfactory results, but this approach frequently proves to be infeasible without the longwall downtime, i.e. without the loss of coal production.

Theoretical effectiveness of the inertization process is guaranteed if the applied inert gas has adequate flammability factor, i.e. mitigates the fire hazard. The flammability factor as calculated by the following formula:

$$K = 4 \cdot C + H + 4 \cdot S - 2 \cdot O - N - 2 \cdot Cl - 3 \cdot F - 5 \cdot Br \tag{1}$$

must meet the requirement:

$$K \leq 0 \tag{2}$$

The inert gases include such substances as sulphur dioxide, water steam, fume gases, nitrogen and carbon dioxide.

The inert gases that have been already used in the Polish mining industry exhibit the following flammability factors: fume gases – K = -1.7, nitrogen – K = -2, carbon dioxide – K = 0. One can note pretty significant difference of the parameter value between the gases that are currently in use, i.e. between nitrogen and carbon dioxide. From this viewpoint it is obvious that nitrogen is definitely a better inert gas. However, there are also other properties and factors that decide about suitability of a specific agent for prophylactic purposes.

Fire-extinguishing properties of inert gases consist firstly in dilution of air and reduction of oxygen content to the concentration value when combustion processes are disabled [12]. For most of combustible materials boundary limit for oxygen falls into the interval between 12-16%, whereas the exact value depends on the specific inert gas. For instance boundary (minimum) threshold values of oxygen content are: in case of burning coal the maximum content of oxygen (O_2) is 12 % at presence of nitrogen and 16 % when carbon dioxide (CO_2) is used as the inert gas. On the other hand the respective values for burning methane amount to 13 % at presence of nitrogen and 16 % for carbon dioxide.

Comparison of the most important characteristic of nitrogen and carbon dioxide with reciprocal characteristics of water proves to be quite interesting (Table 5).

Table 5. Selected characteristics of water, nitrogen and carbon dioxide

Agent	Density ρ	Relative density as compared with air ρ / ρ_p	Specific heat c	Coefficients	
				of thermal conductivity λ	of thermal expansion β
unit	kg/m^3	-	J/kg·K	W/m·K	10^{-3}K
Nitrogen – N (lat. *Nitrogenium*)	1,146	0,967	1039,6 (= 0,249 [cal/(g·^{o}C)])	0,0257	3,35
carbon dioxide – CO_2	1,811	1,518	843,8 (= 0,202 [cal/(g·^{o}C)])	0,0166	3,35

water – H_2O (hydrogen dioxide)	999,7	843,628	4175,4 (= 1,0 [cal/(g·°C)])	0,607	0,257

Density ρ of agents that is calculated by the following formula

$$\rho = \frac{m}{V}\text{, kg/m}^3 \quad (3)$$

where: m - weight, kg

V - volume, m^3

indicates that delivery of carbon dioxide and water shall always lead to natural flow of the agent downwards on even slightest slopes of ground and filling of all possible cavities and basins, whilst the phenomenon is more typical for water. On contrary, nitrogen shall tend to hover up as it will be drifted up by the atmosphere (air, goaf gases) and transferred alongside the same direction as that atmosphere migrates.

Transfer of heat from locations of fires or coal self-heating can vary in quite broad ranges (Table 6).

Table 6. Methods of heat transfer

Method	Mechanism	Criterion of occurrence	Macroscopic phenomena
Conductivity	Stochastic movements of particles	Occurs at whichever temperature gradients	No specific phenomena are visible
Convection	Macroscopic movements of hot and cold areas within the medium, usually caused by unbalanced density	Occurs in gases and liquids with sufficient temperature gradient	Visible streams, bubbles, etc.
Radiation	Emission of electromagnetic waves by hot materials	Occurs under whichever conditions but plays an important role only in the temperature is high enough	Shining of hot materials

Specific heat c of the agent in question (Table 5) informs how effectively the heat emitted in hazardous locations can be captured by the inertizing agent. The total amount of heat Q that can be taken over by the agent is calculated by the formula:

$$Q = c \cdot m \cdot \Delta T\text{, J} \quad (4)$$

Therefore, amount of the heat is directly proportional to the specific heat c, and weight of the heated coal as well as temperature differential ΔT between the inertizing agent and the heated body of coal. The above values (Table 5) disclose that the values of specific heat for both nitrogen and carbon dioxide are quite similar but they are nearly four times less that the specific heat of water, which is undoubtedly the best agent for heat capture and transfer.

On the other hand the coefficient of thermal conductivity λ directly affects the intensity of the heat capturing process. In accordance with the formula:

$$\frac{Q}{\Delta t} = \lambda S \frac{\Delta T}{L}\text{, W} \quad (5)$$

where Δt – time interval, s, the intensity of heat transfer is directly proportional to the coefficient of thermal conductivity λ, contact surface S *as* well as temperature differential ΔT between the area of self-heating and the area where the agent contacts the coal. It is also inversely proportional of the gap width L that separates the two layers.

The presented results (Table 5) reveal that under the same circumstances the intensity of heat transfer by nitrogen and carbon dioxide, which exhibit similar characteristics in that aspect, shall be more than twenty times lower that the same parameter of water.

The second of the coefficients (Table 5), i.e. thermal expansion β (by volume) informs that volume V_0 of delivered agent shall increase to the volume of V_1 that can be calculated by the formula:

$$V_1 = V_0\,[1 + \beta\,(T_1 - T_0)],\ \mathrm{m}^3 \qquad (6)$$

where: T_0 - initial temperature of the volume V_0,

T_1 - temperature of the volume V_1.

The volume increase shall be directly proportional to that coefficient as well as the temperature differential between the agent and location of the self-heating process. The gathered figures (Table 5) show that capability of nitrogen and carbon dioxide to increase their volumes is thirteen times higher than the corresponding value for water.

5 ADVERSE SIDE EFFECTS RELATED TO APPLICATION OF INERT GASES

Safe use of inert gases for de-stimulation of the coal self-heating process and extinguishing of fires must be thoroughly analyzed in order to determine other results, even adverse ones, of application thereof. First of all, these include selection of places for gas application and amount of inert gases that can egress from goafs (or dammed areas), back to the operated mining excavations. In addition, it is necessary to estimate how much of goaf gas shall be expelled by the delivered inert gases. Amount of such “expelled” gas shall firstly depend on the aforementioned thermal expansion coefficient as well as on specific circumstances of the inertization process, related to locations of hazards and degree thereof.

Let us assume that hazard of endogenous fires occurs in goafs, temperature of the self-heating location is lower of the coal ignition temperature that amounts to t_z = 300°C and local circumstances allow to apply inert gases and/or water. In case of water spraying the desired effect shall be achieved either by accurate and direct targeting of water stream to the location of the self-heating coal body or by flooding of the entire area by increasing of water level in goafs. In the both cases only a small amount of water shall directly contact the location of coal self-heating with the (assumed) high temperature. Majority of water shall fill goafs with temperature that is quite similar to the temperature of the rock mass (e.g. 45°C). It is why the assumption can be made that water temperature shall increase by not more than $(T_1 - T_0) \cong 25^{\circ}\mathrm{C}$. Under such conditions, in accordance with the formula (6), eventual volume of water V_1 shall be $1.006 \cdot V_0$ of the initial volume. When adsorption of water by the rock mass (soaking with water) is taken into account, no increase of water volume will prove to occur.

If nitrogen or carbon dioxide is used for the same circumstances of coal self-heating, a defined volume of goaf gases shall mix up with the outcast airstream where the released volume of such gases shall be higher than the volume of delivered inert gases. Relatively high value of the thermal expansion coefficient shall bring about to significant increase of eventual volume of inert gases. In accordance with the formula (6) the final volume V_1 shall amount to $1{,}083 \cdot V_0$ of the initial one.

Results of that thermal expansion of gases can be considered as so called adverse side effect that in case of fire hazard in goafs leads to outflow of carbon oxide and carbon dioxide and, under specific circumstances, even some methane. When inertization is carried out in a non-insulated region the described phenomenon may lead to concentration growth of those gases in the outcast airstream whilst in case of insulated areas – increase of overpressure or drop of negative pressure along with simultaneous concentration growth of these gases in areas behind the insulating dams.

Adverse side effects shall look like in a diverse manner when inertization is applied to extinguishing of coal fire. Use of carbon dioxide may lead to two types of adverse side effects. The fist one shall take place if no contact of carbon dioxide with the fire occurs. Then the volume increase of the delivered carbon dioxide is much higher as the thermal expansion is directly proportional to the large temperature differential between the temperature of delivered carbon dioxide and the ambient temperature of the fire location. Application of nitrogen leads to nearly the same effects. But, when direct contact of carbon dioxide with burning coal takes place due to whichever reasons, then an endothermic chemical reaction occurs that may be dangerous [12]

$$CO_2 + C \rightarrow 2CO - 175{,}6\ ,\ \mathrm{kJ/mol} \qquad (7).$$

The reaction of carbon dioxide reduction that is exhibited in the above equation depends on the temperature of burning coal. For instance, at the temperature of 1,000°C the entire carbon dioxide shall be reduced to carbon oxide. Hence, the increasing concentration of carbon dioxide can exceed the lower explosive limit, i.e. 12.5 % of CO. Consequently, the process where mixture of explosive fire gases is formed, can be speeded up. The process is defined by the Le Chatelier's factor in the following formula:

$$L = \frac{\frac{CH_4}{5} + \frac{CO}{13} + \frac{H_2 + C_mH_n}{4}}{} \geq 0{,}6 \qquad (8)$$

where concentration of oxygen in the mixture is simultaneously defined by the relationship:

$$O_2 \geq (O_2)_{\min} = \frac{12CH_4 + 6CO + (H_2 + C_mH_n)}{CH_4 + CO + H_2 + C_mH_n} \qquad (9)$$

It is the reason why uncontrolled inertization with carbon dioxide in locations of fires should be avoided. However, contact of nitrogen (inflammable gas) with centres of fires shall lead to no similar chemical reactions that cause such adverse side effects.

On the other hand, water in direct contact with fire evaporates and is converted into water steam, where 1,700 litres of steam (1.7 m^3) is produced of a litre of water. It results in massive increase of air volume (when the excavation is in fire) or the volume of goaf gases (when fires set off in goafs) with further expelling of volumes into operated excavations.

All the above deliberations should make clear that awareness of every adverse side effect related to inertization and delivering of water is extremely important in the viewpoint of occupational safety and all the associated hazards must be taken into account when such operations de-stimulating or fire-extinguishing operations.

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RESUME

Analysis of reasons that initiate the self-heating process of coal makes it possible to identify factors that stimulate the phenomenon and properly address all the related mitigating and de-stimulating efforts.

Nitrogen, and recently carbon dioxide, represent the inert gases that more and more frequently used due to their availability and wide scope of possible application with no downtime of mining excavations or breaks in coal production.

However, some properties of inert gases and water may, under specific conditions, lead to adverse side effects that are getting more intense with temperature growth of the locations where the coal self-heating process occurs (usually within non-dammed areas) or real fires are in progress (usually within dammed areas). These side effects include:

- increased volume of delivered gas – which brings about to more intense "expelling" of goaf gases into the outcast air stream or to variations in differential pressure behind the insulating dams,
- reduction of carbon dioxide into carbon oxide; as the reaction runs at very high temperature of burning coal, it is conducive to formation of explosive mixture of explosive fire gases and accelerates the process,
- evaporation of water and formation of huge amounts of water steam when water contacts the burning coal, which increases amounts of gases that are expelled from goafs to operated excavations.

Awareness of every adverse side effect related to inertization and delivering of water is extremely important in the viewpoint of occupational safety and all the associated hazards must be taken into account when such operations are anticipated.

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