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Dynamics of motion of gases from a source of spontaneous combustion of coal in mine workings

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Abstract

The object of this paper is to study the specificity of the dynamics of carbon monoxide in mining to determine the location of the source of coal self-heating or spontaneous combustion. The Fire Dynamics Simulator software package was used to model the gas hazard of coal mine workings. Given the typical details for the western coal basin of Donbas geometric dimensions of workings, properties of coal, etc., a model of a fragment of emergency mining of a coal mine was created, which allows for the display of geometric and physical similarity to processes in actual mine workings. The results of the simulation for the studied scenarios with different air supply systems related to the detection and location of sources of self-heating or spontaneous combustion in the coal mine workings were obtained and analysed. It was established that low-density fire gases are concentrated in the vault of the workings, where they slowly dissolve in the air, with the dissolution process being linear. It was revealed that air velocity up to 0.67 to 0.7 m/s contributes to the formation of fire gas flows, which move towards the ventilation flow, almost without mixing, which is referred to as bifurcation. Numerical parameters of fire gas dynamics in near-real conditions were established, which can become a basis for the detection and location of sources of endogenous thermodynamic processes in mine workings.

Keywords:

underground fires; simulation; carbon monoxide; Fire Dynamics Simulator; mine working; coal; spontaneous combustion

1. Introduction

Underground fires in coal mines significantly complicate mining operations, lead to the loss of mineral reserves and expensive coal mining equipment prepared for extraction. They also cause enormous economic damage associated with fire extinguishing. Extinguishing endogenous fires caused by the spontaneous combustion of coal in hard-to-reach places is especially complicated.

Statistics from the Coal Mining Rescue Service show that over the past decades, the cost of a single fire from coal spontaneous combustion ranged from 2400 to 4100 man-hours, while the average for a single fire in industry ranged from 850 to 1350. The economic damage from endogenous fires during this period ranged from 2.7 to 112.8 million UAH (0.09 to 3.76 million EUR) (**PMMRS, 2016**).

A significant proportion of endogenous fires, from 33% to 70%, occur annually in the worked-out areas, which makes it difficult to detect them at an early stage of development, and locate the foci coordinates (**CHPMMRS, 2016**). Due to the lack of reliable data on the state and location of the fire, the efficiency of supplying fire-extinguishing substances is sharply reduced, and insulation methods or insulation-based combined methods are used for extinguishing.

Due to the onset of hostilities in Donbas, the situation at the coal mines in the territory controlled by the Ukraine have become more complicated due to the fact that the equipment for assessing the propensity of layers to spontaneous combustion, for conducting an operational forecast of coal self-heating and for other studies has been left in Donetsk. In this regard, the task of protecting Ukrainian mines from the threat of self-heating

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and spontaneous combustion of coal has become particularly urgent.

The idea of the study is to substantiate the possibility of expanding the capacity of existing gas protection systems of mines in relation to the location, primarily, foci of self-heating and spontaneous combustion of coal, as well as other sources of fire gases.

2. Overview of Recent Studies and Publications

According to the requirements of the current coal industry regulations (**SRLP 1.1.30-4.01-93, 1993**), the approved ventilation regime must be stable, controlled, and reduce the speed of fire and the size of the combustion zone should an underground fire occur. When choosing a ventilation mode and method of its implementation, the following factors should be considered: the location of occurrence of the accident and the size of the affected area; the intensity of the release of combustible and explosive gases into the workings of the accident site and adjacent areas, and the estimated time they reach explosive concentrations; the intensity of the internal sources of the draft formed as a result of the accident (thermal depression, gravitational pressure of methane), and a number of others. However, in order to comply with the statutory requirements, it is necessary to have operational information about the location of the fire, the consumption of fire gases, etc. In emergency conditions, this requires the use of human resources, considerable time, and is often impossible. The way out of this situation may be to use gas shields to obtain the necessary information that can ensure the timeliness and credibility of the required data (**Vovna et al., 2017**). However, the existing gas shield systems do not meet the necessary requirements; their improvement requires additional scientific justification.

A number of works by authoritative scientists are devoted to the study of coal spontaneous combustion processes. There are many factors that influence the tendency for coal to spontaneously combust in coal mines. Pyrite can promote the risk of this phenomenon. This promotion is accelerated by the combination of pyrite and moisture content at the same time (**Saffari et al., 2019**). In this research, the accelerating effect of reactive pyrite and moisture content on coal spontaneous combustion was measured experimentally. For this purpose, a new experimental apparatus was assembled and made. The results show that pyrite content can linearly accelerate the coal spontaneous combustion process, while moisture content under 20% increases it, and if the moisture exceeds 20%, the rate of this process is reduced. The results of this research are helpful in the assessment and management of coal spontaneous combustion issues in coal mines.

The European method of current control of endogenous processes makes it possible to detect the fact of the appearance of a source of self-heating or spontaneous combustion of coal in the mining area. This requires the availability of information about the relative (%) and absolute (l/min) content in the air flow of the so-called indicator gases, carbon monoxide (CO) or hydrogen (H_2) (**Gamiy et al., 2020, Gamiy et al., 2019**). Thus, the issue is to consider a purely ventilation task to determine the nature of the release of fire gases from the hearth and their motion along the working.

In our opinion, the first step in this direction is to reproduce the formation of the combustion source and the dynamics of motion of fire gases in the workings by computer simulation of this process. This approach to the study of gas dynamics in mines is quite common in world mining science; there is a significant number of studies of ventilation flows in the network of mine workings.

The feasibility of large eddy simulation (LES) approach in combination with the model of partially premixed combustion (PPC) for simulating transient combustion events occurring in fuel vapour clouds is considered (**Hu and Trouve, 2008**). The test setting corresponds to controlled ignition followed by explosive combustion in a room filled with vertically stratified propane mixtures in air, both with and without ventilation, as well as with and without ventilation resistances. In general, the comparison between numerical results and experimental data varies from fair to good and confirms the feasibility of LES explosive combustion treatment. However, the processes corresponding to our objective are not considered in this paper.

Computer models of fire in underground mines have been used to analyse and assess the effects of fire scenarios on the evacuation process and mining safety (**Adjiski et al., 2019**). The results of the methodology that implements the simulation are presented, several scenarios reproduced in a 3D model to demonstrate the distribution of combustion products through the mine ventilation network. The simulation results are analysed and potentially dangerous fire scenarios are identified. This paper did not consider the nature of the propagation of the cloud of fire gases in the cross-section of the working, as well as the nature of their mixing with the ventilation air.

Two types of combustion were considered: one exogenous fire consisting of coal material, and the other used the two most common fuel sources found in the coal mine: coal and wooden sleepers (**Trevits et al., 2009**). Coal test information was used as a model for an actual fire. The article describes the combustion modes, provides an idea of the characteristics of flame propagation, and presents the results of simulation work. Unfortunately, such studies do not meet the conditions for the formation and development of foci of coal self-heating and spontaneous combustion.

Simulations of three critical fire scenarios from solid materials in mines were carried out: in underground mining, as a part of explosives and on the conveyor belt

(**Brake, 2013**). The impact of fires on evacuation and flooding strategies of a mine was considered. Some general principles for improving the design of the ventilation circuit were also recommended. The scenarios did not correspond to the dynamics of the formation and the development of endogenous fires.

There is an analysis of several scenarios of fire in underground mining, taking into account the main environmental variables: airflow, temperature, oxygen and pollutants (**Fernández-Alaiz et al., 2020**). The evolution of fire over time along the working and its cross-section was determined, important fire trends were found based on the ratio of airflow and fuel. The results can also be a very useful tool for studying the danger of possible emergencies or the potential impact of fire in similar environments. These results are close to the direction of our study, but they relate to the evolution of exogenous fires and this methodological approach cannot be used to study the processes associated with coal self-heating and spontaneous combustion.

An approach to simulating fires in underground mines was proposed, the advantages and purposes of fire simulation, as well as the limitations of the study, were assessed (**Prosser and Ruckman, 2010**). A risk assessment plan was provided, as well as the simulation and development of strategies to minimize the probable risks associated with fire. However, the nature of the distribution of gases in the cross-section of the mine and their dissolution when moving through the mine was not considered.

Of interest is the study of the law of smoke inverted flow in the middle of a fire in a metal mine, software was used to model the fire, and an actual mine was used as a study basis to create a model that includes a middle section and a ramp (**Tian et al., 2020**). The results of the study show that the range of smoke inverted flow in the middle section of different capacities of the fire source can reach 8 to 30 m, and the wind speed in the middle section has a significant effect on suppressing the reverse flow of flue gases. Such results are difficult to extrapolate to actual workings with existing ventilation parameters.

There is a comparative simulation and theory of simulation technologies (**Binbin, 2011**), as well as a physical model of the spread of fire smoke at a subway platform, and the calculations were used as a basis for studying the spread of fire smoke in the projected subway platform (**Adjiski, 2014**). In the said simulation, the parameters of the smoke source correspond to the development of the source of exogenous fire, the geometric dimensions of the working, and the topology of the ventilation paths differ significantly from the coal mine.

Of great interest is the study of three critical stages of the smoke propagation process, the local phenomena of counter-gas flows, the so-called bifurcation. Critical stages of smoke motion and its reaction to the ventilation network were observed by means of 3D-CFD analysis. It is possible to expand the range of smoke propagation forecast for a wide range of airflows, fire intensity, slopes and minefield layouts to create three different CFD fire scenarios, and further observe the critical stages of smoke propagation effects (**Yuan et al., 2019**). The authors encountered this phenomenon during actual emergency response. It needs to be closely studied for the conditions of coal mines.

The generalization of the information shows that computer simulation of ventilation processes, including emergency ventilation modes, is a widespread and reliable study method with near-field results. The known papers do not reflect the peculiarities of the development of sources of self-heating and the spontaneous combustion of coal. Thus, the problem of disclosing the mechanism of the formation of fire gases in the hearth of coal self-heating and spontaneous combustion, as well as the distribution in the cross-section and the dissolution of air when moving along the working remains unresolved. Of greatest interest is the dynamics of the so-called indicator gas, carbon monoxide, which reflects the qualitative and quantitative side of the process of development of endogenous fire, and can also help determine the location of the source of spontaneous combustion.

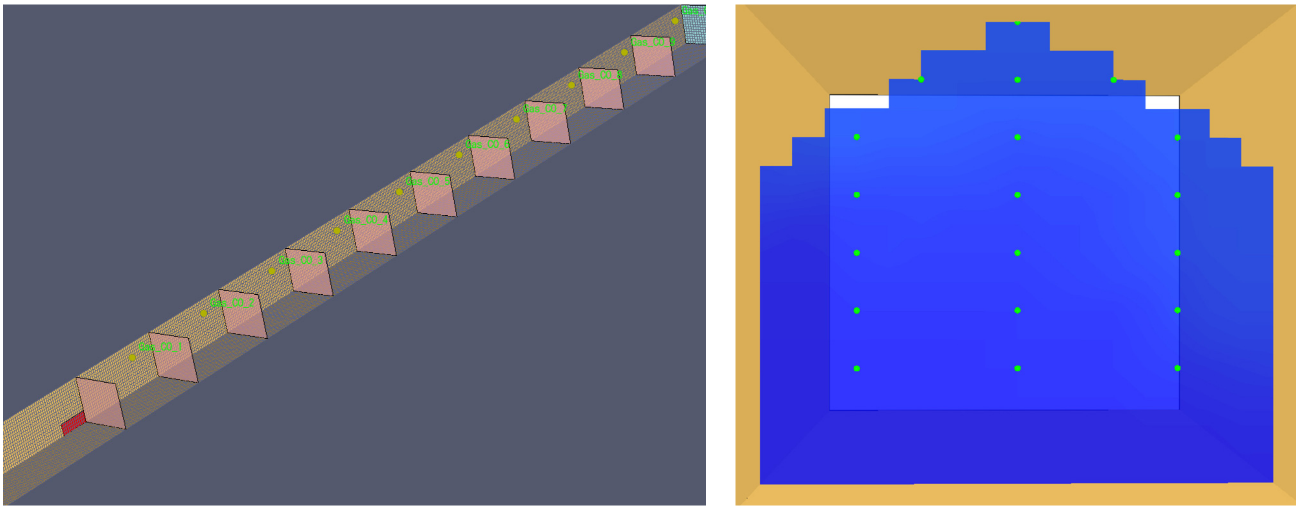
The objective of this paper is to reveal the dynamics of fire gases, primarily CO, in a mine working, as a basis for determining the location of the source of coal self-heating or spontaneous combustion. CO was chosen as the indicator gas because it is very toxic, and mine gas control equipment usually widely uses sensors to measure carbon monoxide.

To achieve this objective, the following tasks were accomplished:

- the most probable scenario of the occurrence and formation of fire gassing of coal mine workings was determined;
- the approach to simulation of gas hazard of workings of coal mines based on known ways of gas flows simulations was chosen;
- the initial data for simulation was defined;
- a 3D model of a fragment of an emergency coal mine was created;
- the results of simulation for the studied scenarios related to the detection and location of sources of self-heating or spontaneous combustion in the workings of a coal mine were obtained and analysed.

3. Methods

The main modern approaches to the study of gas hazard in the workings of coal mines, taking into account the effects of ventilation, are a computer simulation using computational fluid dynamics (CFD), which are divided into programs:



a) b)

a) red rectangle - spontaneous combustion place; yellow dots – sensors
b) green dots - sensors

Figure 1: Schemes of arrangement of measuring cross-sections on length (a) and sensors in cross-section (b) of the working.

- own-developed;
- open source programs, including specialized ones (Fire Dynamics Simulator);
- commercial software packages (ANSYS, FlowVision).

The task of the study does not provide for the development of an own-developed software package. The scientific basis of most CFD models used is the simulation of turbulent flows based on the averaged Navier-Stokes equations. They are quite accurate, publicly available, are not computationally expensive, and are widely used to solve engineering problems.

Engineering software packages such as ANSYS, FlowVision are a commercial product, and the license costs much more than the cost of one calculation work.

Based on the specifics of the study, it was decided to use the software package Fire Dynamics Simulator (FDS) based on the LES method. This approach will allow for the development of both separate models for hazards of gas, dust and fires, taking into account the effects of ventilation, and complex ones, for example, simulating the hazards of gas, dust, and fires in gas pollution of the workings. With the advent of sources of self-heating and spontaneous combustion, the most informative (indicator) is the dynamics of formation and distribution of carbon monoxide (CO). This process is the subject of this study.

Gas pollution of workings is determined by several factors, the main of which being as follows: the form of the working, its cross-section area, consumption of ventilation air and fire gases, and the length of the working.

Currently, up to 98% of underground mine workings have a vaulted cross-section. Thus, at the first stage of studies, it is expedient to consider simulating the dynamics of the motion of gases in a horizontal working of a vaulted cross-section.

The most common are the workings with a cross-section area of about 12 to 18 m^2. Workings with a cross-section of about 22 m^2 are carried out for intensive ventilation of mining faces. Three main dimensions are considered in the simulation, namely: 12.8; 18 and 22.5 m^2. These values correspond to typical mine workings.

From practical experience, it is known that most often, the range of air consumption in actual preparatory workings makes up 500 to 1500 m^3/min, therefore, three basic options are considered in the simulation, namely: 500; 1000 and 1500 m^3/min. It is difficult to detect the location of foci in workings filled with such equipment as conveyors, substations, hydraulic equipment, etc. The possibility of finding sources in a limited area up to 100 m is considered.

Data for simulating the source of coal spontaneous combustion are accepted as typical indicators of coal of the average stage of metamorphism (**Ryabtsev, 1960**). The lower heat of combustion of 30 MJ/kg corresponds to the properties of coal, which mainly occurs in the western part of the Ukrainian Donbass.

Based on the initial data, three variants of the 3D model corresponding to a 200 m fragment of workings of different cross-section planes were made, with three options of ventilation considered for further use in configuration and further use as design areas. The size of the cell for the construction of models of mine workings was chosen from 0.15 to 0.25 m. It was specified that the source of spontaneous combustion was located in the middle of the working on the left side in the direction of airflow. Measuring sensors were installed along the length of the mine every 10 m from the source of spontaneous combustion under the roof, as well as along the cross-section of the mine (see **Figure 1**).

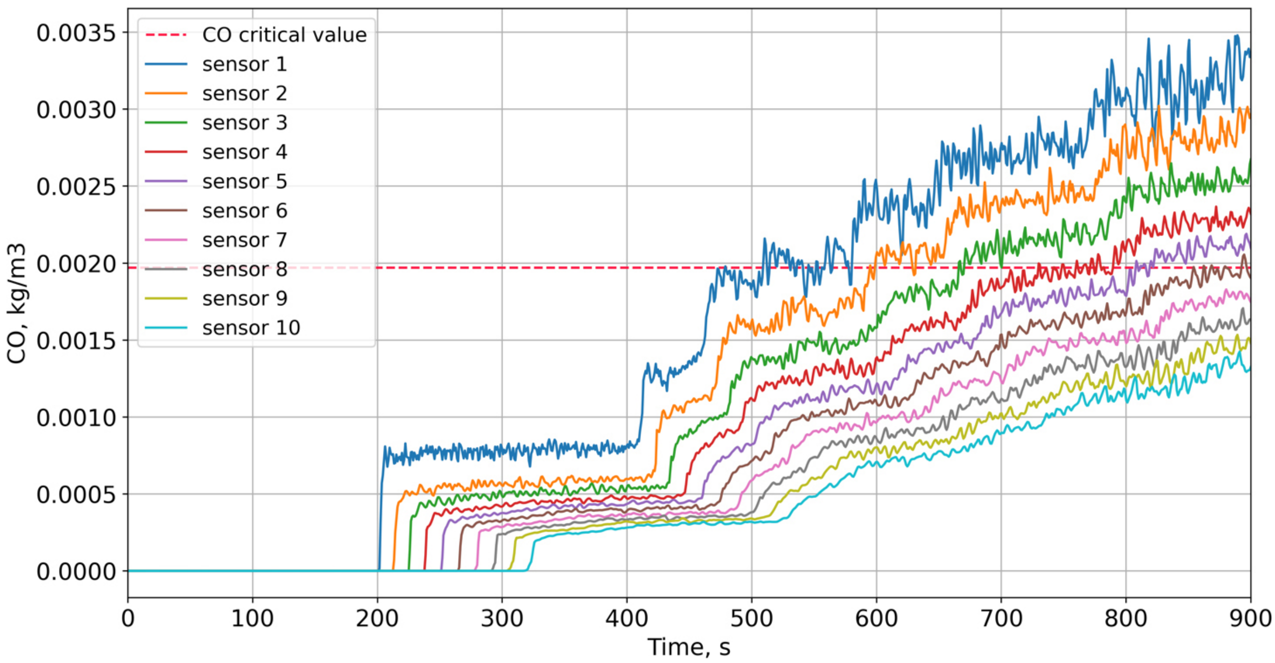


Figure 2: The dynamics of CO in a working with an area of 12.8 m^2 and airflow of 500 m^3/min

4. Results and Discussion

The simulation is performed with the maximum similarity to actual mine workings, which allows for the extrapolation of the results to the conditions of operating mines with a high degree of reliability. The mechanism of fire gases motion at a distance of 100 m from the source of spontaneous combustion of coal is revealed.

The general picture of the motion of fire gases in the mine resembles smoke coming out of a chimney, and its subsequent motion in the wind flow. Fire gases have a higher temperature than ventilation air, and, therefore, a lower density, thus, they move to the vault of the mine workings where they move in a separate flow, slowly dissolving in the air. It follows that to detect early signs of endogenous fire, it is necessary to control the composition of gases in the upper part of the cross-section of a working.

With the help of the FDS program, it is possible to consider the dynamics of gas distribution, namely CO, along the working over a period for each of the proposed scenarios. A specific example of a calculation for sensors installed at the top of the vault is given below (see **Figure 2**). The dynamics of CO at the site 0 to 95 m from the source of the fire in the working with an area of 12.8 m^2 and airflow of 500 m^3/min was evidenced by the sensors located at the top of the vault. The dashed line indicates the CO level that exceeds the MPC at the workplace.

It can clearly be seen that the larger the distance from the source of spontaneous combustion, the less the CO content in the air surrounding the sensor. This can be explained by the gradual dissolution of fire gases in the environment due to turbulent diffusion. This phenomenon is the basis for establishing the dependence that allows for the establishment of the location the fire gases come from to the working, thus, finding the source of spontaneous combustion.

The greatest interest is the study of the mechanism of distribution of indicator gas, carbon monoxide (CO), in the vault of a mine where the main part of fire gases is concentrated. For this purpose, seven points of calculation of gases located in the upper part of the working were selected (see **Figure 1b**), and the average value was obtained. For each of the simulated cross-sectional dimensions of the workings (12.8; 18; 22.5 m^2) the dependences of the change in CO content at a distance of 100 m from the source of spontaneous combustion (see **Figure 3**) when supplying a ventilation jet of 500, 1000, 1500 m^3/min were obtained. Almost all obtained dependences have high statistical indicators (R2 is not less than 0.75).

At this working stage, the process of dissolving carbon monoxide in the vault is linear. In this case, the greater the supply of air in the working stage, the more intense the decrease in CO content in the vault. Establishing this dependency allows for locating the source. To this end, it is enough to carry out not less than two measurements of gas composition in the vault. Guided by the linear dependence of the distribution of gases in the vault of the working, the expected location of the source of the endogenous process is plotted.

In general, the equations that describe the dynamics of the CO content in the vault of the workings are expressed as follows (**Equation 1**):

$$c_q = -k \times 10^{-6} + b \tag{1}$$

Where:

c_q – CO concentration in the air (%),
k – the coefficient of the equation,
b – a free term of the equation.

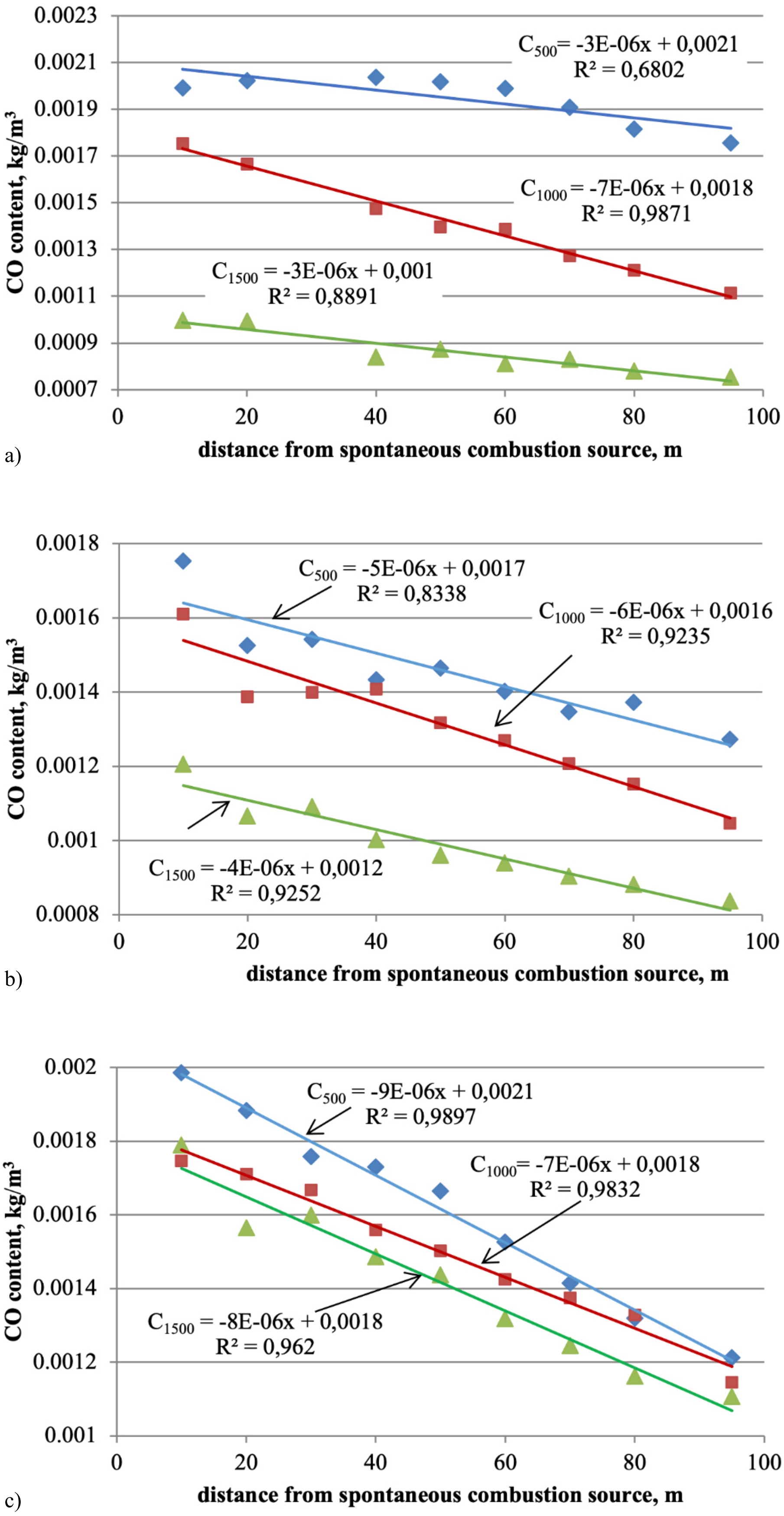
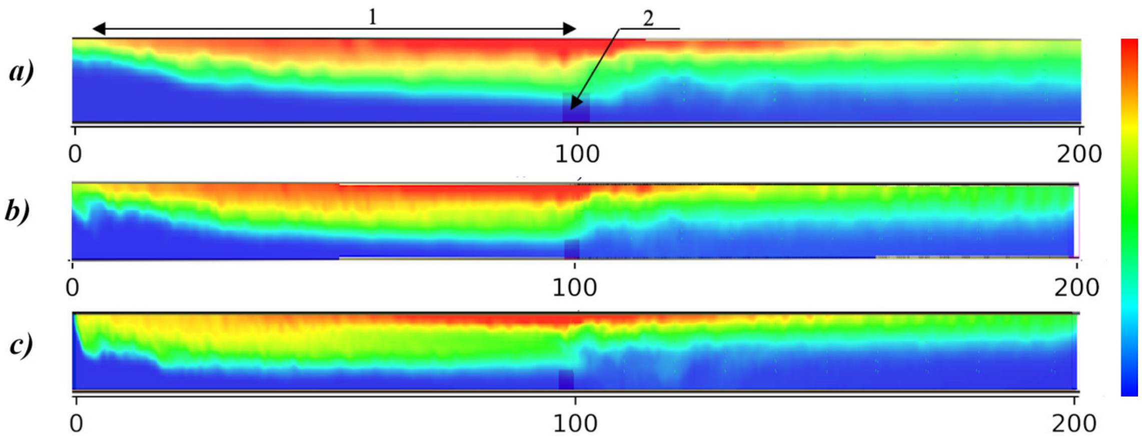


Figure 3: The dynamics of carbon monoxide (CO) in the vault of workings with a cross-section area of, m² a -12.8; b - 18; c - 22.5



1 – bifurcation zone; 2 – source.
a – 12.8, m²; *b* – 18, m²; *c* – 22.5, m².
Colour legend: from 0.00 to 4.00 kg/m³ * 10^{-3} (Smokieview slice of CO spreading).

Figure 4: Formation of bifurcation flow 1200 s into the fire and air supply of 500 m³/min in the workings with different cross-section areas

The analysis of the equations obtained according to the simulation results shows that for a working of a certain cross-section plane, the coefficients of the equations are close in magnitude. The arithmetic mean value of the coefficients for the working with S=12.8 m² is equal to k_c= -4.3, with S=18 m² to k_c= -5, with S=22.5 m² to k_c= -8. The size of the coefficient of the equation in the geometric sense should be understood as the angle of the graph function relative to the horizontal axis. The higher the coefficient, the steeper the incidence of the graph straight. A minus sign in front of the coefficient indicates a decrease in the concentration in the direction of gas motion. In the physical sense, the graph slope reflects the rate of change of CO concentration in the air. The free terms of the obtained equations have a relatively narrow range of fluctuations, from 0.001 to 0.0021.

It has been established that at an airflow rate of 500 m³/min, the CO concentration begins to increase from the fire source in the opposite direction of air supply (see **Figure 4**). The bifurcation of gas flows is formed in the working when a part of the fire gases counters ventilation flow practically without mixing. In a certain place, fire gases, giving off part of the heat, go down and start to move together with the ventilation flow. As the simulation results show, the length of the bifurcation zone depends on the cross-section area of the working, other indicators being equal. Thus, with an air supply of 500 m³/min twenty minutes into the fire, the length of the bifurcation zone was about 48 m in the working with a cross-section of 12 m² (see **Figure 4a**), the zone size was about 90 m with a cross-section area of 18 m², and 95 m with 22 m². However, in workings with a larger cross-section (see **Figure 4 b, c**) a decrease in the concentration of gases of a relatively smaller cross-section was observed (see **Figure 4 a**).

Table 1: The ratio of air flow (Q) to the cross-sectional plane of the mine workings (S)

Air flow, m³/min	Cross-sectional plane of the mine workings, m²		
	12.8	18	22.5
500	39	27.8	22.2
1000	78.1	55.5	44.4
1500	117.1	83.3	66.7

* the ratio B = Q / S at which the phenomenon of bifurcation was observed in the mine workings is highlighted in colour.

We can assume that the ratio of air flow affects the cross-sectional plane (B = Q / S), which in larger workings has a lower value (see **Table 1**).

From the table data follows that at a ratio B = 39 the bifurcation is shown in the smallest size of the mine workings (see **Figure 4a**). At a lower ratio, the bifurcation zone size increases. In the case when the ratio B = 44.4, bifurcation is absent. Thus, it can be argued that the "bifurcation point" for the studied conditions is within B = 40 ... 42. According to its physical meaning, the indicator B, which has a dimension of m/min, is the calculated or average speed of ventilation air in the mine workings. If the speed does not exceed 40 ... 42 m / min, or 0.67 ... 0.7 m / s, then there are conditions for the bifurcation process.

The disadvantage of this study is that it does not take into account the clutter of cross-sections of workings with equipment such as conveyors, pipelines, cables, starting equipment, etc., that can disrupt the linearity of the gases and the accuracy of the location. This is the subject of further studies. In addition, in the future it is advisable to take into account the impact of mounting, especially in the vaulted part of the mine working. Mounting frames protruding outward from the production contour form vortices that change the flow of air.

5. Conclusions

In this work, to study the dynamics of the movement of carbon monoxide in mining workings to determine the location of the source of self-heating or spontaneous combustion of coal was simulated using the software package Fire Dynamics Simulator. Given the typical details for the western coal basin of Donbas geometric dimensions of workings, properties of coal, etc., a model of a fragment of emergency mining of a coal mine was created, which allows for the display of geometric and physical similarity to processes in actual mine workings. The results of the simulation for the studied scenarios with different air supply systems related to the detection and location of sources of self-heating or spontaneous combustion in the coal mine workings were obtained and analysed. It was established that low-density fire gases are concentrated in the vault of the workings, where they slowly dissolve in air, with the dissolution process being linear. In workings with a larger cross-section area, the dissolution of fire gases in the air is faster. This appears to be logical, since a larger volume of air and a higher coefficient of turbulent diffusion intensify dissolution. Low-velocity ventilation flow can lead to a phenomenon of a bifurcation motion of fire gases. This can result in an erroneous source location, and requires further study. It is of interest to identify such ratios of fire gas leakage and airflow which lead to the so-called "bifurcation point", the onset of the said phenomenon. The initial data used in the simulation are typical for the range of mining conditions of Donbas, thus, the obtained index of 0.67 to 0.7 m/s can be recommended as a first approximation for use as a criterion for actual mine workings.

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SAŽETAK

Dinamika gibanja plinova od mjesta spontanoga samozapaljenja ugljena na radilištima

U radu se analizira posebnost dinamike ugljikova monoksida u rudarstvu kako bi se odredio smještaj izvorišta samozagrijavanja i samozapaljenja ugljena. Uporabljen je programski paket Fire Dynamics Simulator, kojim je modeliran rizik od plina na radilištu rudnika. Ogledno istraživanje načinjeno je na zapadu ugljenih bazena Donbasa uzimajući u obzir geometrijske dimenzije radilišta, svojstva ugljena itd. Stvoren je model za izvanredno rudarenje ugljena u izvanrednim okolnostima koji se može primijeniti na stvarne uvjete (geometriju, fizička svojstva) ugljenokopa. Simulacija je izvedena s nekoliko scenarija opskrbe zrakom s obzirom na smještaj detektora i izvora samozagrijavanja ili samozapaljenja. Utvrđeno je kako su zapaljivi plinovi male gustoće nakupljeni uz svod radilišta, gdje se sporo miješaju sa zrakom tijekom procesa koji je linearan. Prikazano je kako brzina strujenja zraka od 0,67 do 0,7 m/s pridonosi stvaranju toka zapaljivih plinova koji se tada gibaju prema ventilacijskome sustavu gotovo bez miješanja, ali s pojavama bifurkacije. Brojčane vrijednosti dobivene simulacijom za dinamiku zapaljivih plinova odgovaraju gotovo potpuno stvarnim uvjetima, te model može biti temelj za opažanje i smještanje endogenih (unutarnjih) termodinamičkih procesa na rudarskim radilištima.

Ključne riječi:
podzemni požari; simulacija; ugljikov monoksid; programski paket Fire Dynamics Simulator; radilište rudnika ugljena; samozapaljenje

Authors contribution

Viktor Kostenko (doctor of technical sciences, professor): initialized the idea, developed a methodological approach, managed the whole process and supervised it from the beginning to the end. **Yuriy Gamiy** (mag. ing.): set the goal and objectives of the experiment, planned the experiment and formed the initial data for the experiment. **Tetiana Kostenko** (doctor of technical sciences, associate professor): participated in all stages of work, submission and review of the paper and the completion of the literature review, as well as in the analysis of the experimental results. **Sergii Tsvirkun** (PhD, associate professor): created a 3D model of a fragment of mining, modelled fire scenarios, assisted in the visualization of the distribution of gases on an emergency site. **Maksym Udovenko** (mag. ing.): analytically processed the calculation results, constructed graphs, and analysed literary sources of information.