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Modeling the stability of air flows in inclined workings in case of fire

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Abstract

Purpose. Development of a mathematical model and study of the processes occurring during conveyor belt fires in inclined mines to determine the mechanism of air flow distribution under appropriate conditions.

Methods. Practical measurements of the distribution of air flows in an inclined conveyor operated at the mining and processing plant of PJSC ArcelorMittal Kryvyi Rih were carried out. Based on the obtained data, a mathematical model was created, which was then used to perform Computational Fluid Dynamics (CFD) modeling of gas flows in the mine under normal conditions and in the event of a fire with a thermal capacity of 9 MW.

Findings. The study reveals the peculiarities of gas flows during the combustion of a conveyor belt in inclined workings, as well as the influence of turbulence on the flow, changes in the density of gases during heating, and the impact of gravity on the distribution of gases in the cross-section and along the length of the workings. A fire centre with a heat output of 9 MW has a significant impact on the distribution of air flows. The phenomenon of thermal expansion results in a 59.2% increase in the volume of gases behind the fire. The thermal expansion of gases and their low density have a significant impact on the formation of gas flows in inclined workings. As the jet moves away from the centre of the fire, the velocity of the jet gradually increases, reaching a value of 12.4 m/s. This results in a notable alteration in the distribution of total pressure across adjacent workings, accompanied by an increase in flow turbulence. Consequently, the mass of air exiting the right branch is observed to have a five-fold increase in comparison to the pre-fire state. The overturning of the jet from the left branch of the workings gives rise to the exclusive distribution of combustion products along the right branch.

Originality. The study helps to understand the mechanism of jet overturning and the peculiarities of the distribution of combustion products in case of fire in inclined conveyor workings.

Practical implications. The results of the research allow us to predict the probability of fire, identify the most dangerous areas for fire, and plan the most rational actions for firefighting in specific unique conditions.

Keywords: *underground fire, mine safety, ventilation network, mining, Computational Fluid Dynamics*

1. Introduction

1.1. The problem formulation

The mining industry is an important part of the global economy. This industry accounts for approximately 8% of the global economy [1]. In 2021, the share of the mining and metals sector (excluding the coal industry) in the Ukraine's GDP was approximately 38%, in industrial production was 27.3%, and in exports was 34.2%. The proportion of metallurgy in tax contributions to all levels of government is approximately 38% [2]. Concurrently, the mining industry is widely regarded as the most hazardous industrial sector [3]. The analysis of accidents at Ukrainian ore mining and processing enterprises reveals that as the depth of mineral development increases, the use of high-tech and energy-intensive equipment, as well as the increased load on preparatory and stope workings, the potential risk of man-made and natural emergencies rises.

From 2014 to 2024, the units of the State Emergency Service of Ukraine were engaged in responding to 734 incidents that occurred at mining enterprises, both underground and surface facilities. The number of operational visits conducted to eliminate the consequences of accidents and emergencies is presented in Table 1. Fires in underground mines are one of the most challenging emergencies. Between 2014 and 2024, mine rescue units were called out 164 times to deal with the consequences of fires and smoke in mines, accounting for 22.3% of all types of accidents. Mine fires result in the formation of smoke and high levels of toxic gases, as well as drastic changes in the microclimatic conditions in the mine workings. Fires in inclined mine workings can lead to disruption of ventilation in individual sections and a significant part of the minefield.

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Table 1. The number of operational visits to emergency rescue operations by units of the State Fire and Rescue Service of Ukraine

Types of accidents and emergencies	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total
Fires in underground workings and on the surface	7	13	9	22	8	10	18	7	57	5	5	161
The collapse of mine workings, destruction of buildings	2	1	1	–	2	–	–	1	–	–	2	9
Emergencies with people	16	14	23	30	35	19	32	29	15	14	2	229
Road traffic accident	1	1	1	–	–	1		6	–	–	–	10
Shutdown of the main ventilation units	1	1	–	–	–	–	–	–	–	–	–	2
Gas pollution and smoke in mine workings	–	1	–	–	–	–	–	–	1	–	1	3
Demercurization	–	–	34	20	8	7	1	–	–	–	–	70
Disinfection	–	–	–	–	–		31	–	–	–	–	31
Assistance in disaster relief	–	–	–	–	–	5	92	–	–	78	1	176
Events of martial law	–	–	–	–	–	–	–	–	19	22	2	43
Total number of visits to the to the emergency rescue operations (ERP)	27	31	68	72	53	42	174	43	92	119	13	734

As a result, ventilation nozzles may overturn, creating recirculation circuits and convective flows of fumes, gas contamination of the mine workings with fresh air flow, decrease in airflow velocity, etc. [4]. All this can lead to complications in the elimination of accidents and their consequences and, in the worst case, to the death of people.

The study of the processes of fire occurrence and development in mines is an urgent task. The results of the research allow us to predict the probability of fire, identify the most dangerous areas for fire, and plan the most rational actions for firefighting in specific unique conditions.

1.2. Research and publications analysis

The risks associated with multiple hazards in non-coal underground mines were assessed in [5]. Five types of hazards were identified, including cage fall accidents, mechanized transport accidents, fires, mine water intrusion accidents, and roof fall and rock detachment accidents. Of all mine disasters, fires pose the greatest threat to mine safety and often have the most serious consequences. Research on technologies and theories of fire occurrence and prevention in mines has grown significantly and is attracting increasing scientific interest and attention. The work [6] shows that the number of scientific papers on this topic is constantly growing and has a sharp rise, especially after 2015. According to the same study, the main research topics in the field of mine fire occurrence and prevention are “mine fire control technology”, “mine fire mechanism”, “mine fire prediction technology” and “mine fire monitoring technology”. China has the largest number of papers, followed by the United States, Australia, and India [7].

According to [8], mine fires often lead to human casualties and material damage, including such direct hazards as destruction of the structure of air flows and the condition of the ventilation system, burnout of resources, explosion of gases or dust, and deterioration of workers’ health.

In addition, a fire in a mine can lead to such indirect hazards as people’s fear, reduced labor productivity, etc.

The most likely places of fire occurrence are inclined mine workings equipped with belt conveyors – 33.9% and horizontal mine workings equipped with belt conveyors – 17.7%. The main causes of belt conveyor fires are friction against the drum – 24%; heating of combustible fluid in hydraulic transmissions during operation in slip mode due to overload and faulty thermal protection or its absence – 23% [9]. The combustible material is the conveyor belt, which ignites due to friction. The peculiarities of the fire development in the mine conveyors are that the fire spreads by the transfer of combustion to adjacent areas or by the flow of hot gases with a certain direction and rate.

The issues of fire occurrence and development are discussed in detail in [10] and [11]. It has been shown that there are four stages of fire development: ignition, growth, full development, and extinction. The intensity of a fire is determined by the rate of heat release, measured in kilowatts, and the higher the rate of heat release, the more intense the fire.

Fire hazards are characterized by the generation of heat energy and products per unit of time. The factors affecting the rate and nature of heat and combustion products are discussed in paper [12]. The heat release rate (HRR) is a critical parameter for characterizing a fire. It is shown in [13] that an accurate HRR value can be obtained using calorimetric principles. They are based on the consumption of oxygen (O_2) or carbon dioxide and the formation of carbon monoxide (CO). Their advantage is that the amount of energy released per unit mass of O_2 consumed or per unit mass of CO_2 produced is relatively constant for a large number of materials. Paper [14] confirms that the heat release during a fire is a function of the amount of oxygen consumed.

The work [15] shows that the amount of heat released during the combustion of organic substances per unit mass of oxygen consumed in the combustion process is constant and equal to 13.1 MJ/kg. Therefore, to determine the amount of heat released in the combustion process, it is sufficient to determine the amount of oxygen consumed in this process.

The data obtained in [6]-[8] allow us to conclude that other fuels can be used to simulate a fire instead of actual combustible materials that burn in a fire, provided that equivalent heat generation is ensured. At the same time, the amount of oxygen consumed and carbon dioxide emitted does not change. The combustion processes of conveyor belts are discussed in detail in [16]. During the combustion of a rubber fabric belt, a combustion reaction with the fuel C1.9H40O2.6 takes place. According to the work [17], the heat output of the fire during conveyor belt combustion is in the range of 2 to 10 MW.

Methods and technologies for firefighting are described in [18] and [19]. Each mine fire is unique, and the method or combination of methods used to extinguish it will depend on local conditions. One of the key factors influencing the development of fires and the choice of firefighting methods is the nature and power of the airflow in the mine workings. Mine ventilation systems play a key role in providing a safe working environment in a mine.

The assessment of the ventilation system reliability allows for the identification of malfunctions and hidden dangers at an early stage, as well as the provision of a reliable scientific basis for the design and transformation of the ventilation system. The volume and quality of air in each mine working depend on several factors, including the power of the main fans, resistance and air pressure in the workings, temperature and natural air pressure, and the condition of the ventilation structure [20]. The methods for calculating ventilation systems are undergoing constant improvement. New mathematical models, such as those presented in [20] and [21], and calculation methods, as exemplified in [22], are being employed. The application of these new methods can significantly enhance the safety and working conditions in mines. However, other methods are utilized to model air flows in fires.

In the present era, there exist three principal methodologies for fire modeling [23]. Each of these methodologies considers a fire to be a three-dimensional process that develops over time. The initial methodologies were "zone" models, which describe fires in compartments. Each compartment is divided into two spatially homogeneous volumes: a hot upper layer and a colder lower layer. Mass and energy balances are maintained for each layer, and additional models describing other physical processes are added in the form of differential or algebraic equations, as appropriate. The relative physical and computational simplicity of zone models has led to their widespread use in fire scenario analysis. As long as detailed spatial distributions of physical properties are not required, these models are quite reliable.

The growth of computing power and the development of Computational Fluid Dynamics (CFD) have led to the development of CFD-based "field" models used in fire research. These models are based on the conceptual framework provided by the Reynolds-Averaged form of the Navier-Stokes equations (RANS). The application of CFD models has enabled the description of fires in complex geometries and the accounting for a wide range of physical phenomena. However, these models are subject to a fundamental limitation in their application to fire scenarios: the root-mean-square procedure in the model equations. The smallest length scales that can be solved are determined by the product of the local velocity and the averaging time, rather than by the spatial resolution of the underlying computational grid. This approach is unable to account for the evolution of large vortex structures or predict local transient events.

The utilization of "large eddy simulation" (LES) methodologies, which are conducted on finer meshes, has facilitated enhanced temporal and spatial precision in fire simulations [24]. The acronym LES stands for the description of the turbulent mixing of gaseous fuels and combustion products with the local atmosphere surrounding a fire. The fundamental premise of the LES method is that the vortices responsible for the majority of the mixing are sufficiently large to be accurately modeled using fluid dynamics equations. It is assumed that the small-scale vortex motion can either be accounted for approximately or ignored.

To date, a considerable number of simulations of fires in mine workings and tunnels have been conducted using both RANS and LES models. The scope of this paper precludes consideration of all relevant studies; therefore, we will focus on those that seem most relevant to our study.

In discussing fire ventilation methods in the context of fire safety, paper [25] also considers methods for measuring the performance of ventilation systems. A Computational Fluid Dynamics (CFD) simulation of an exhaust ventilation system for smoke control in a building was developed for this case study. The results of this CFD simulation demonstrate that the source of the fire can be effectively eliminated by activating the exhaust system, thereby reducing the risk to the lives of fire victims and the extent of property damage.

The paper [26] presents the results of experimental and computational study of the characteristics of fire initiation and propagation along the upper and lower surfaces of a conveyor belt mounted in a ventilated full-scale experimental fire gallery. A novel modeling approach is presented to accurately represent the observed flame propagation along the conveyor belt surface.

The paper [27] employs a computational model to simulate the evolution of a fire in a transportation tunnel. The distribution of gas temperature along the length of the tunnel is subjected to analysis. The relationship between this parameter and the firepower is elucidated. It is proposed that heptane be used as a fuel for modeling the fire center.

The methodology for calibrating the parameters of the fire and the surrounding space is discussed in [28]. It is demonstrated that calibrating simulations with experimental data is an effective methodology that enables the investigation of the influence of variable parameters beyond the scope of the original experiments. It has been shown that the airflow within the tunnel exerts a considerable influence on the rate of heat release.

To ascertain the effect of the power and location of fire centers on the ceiling temperature of tunnels, a model has been constructed and analyzed according to the methodology outlined in the paper [29]. The results demonstrate that an increased ventilation rate is associated with a reduction in the overall ceiling temperature.

A search of the Web of Science Core Collection for the period from 2010 to 2024 has not yielded any scientific papers on the peculiarities of the processes occurring during the burning of conveyor belts in inclined mine workings. Therefore, as inclined mine workings equipped with belt conveyors are the most likely locations for fire occurrence, further research in this area is required.

1.3. Formulation of the problem

Fires in underground mine workings represent the most complex and most frequent emergencies. The primary indicators for establishing the optimal conditions for mitigating the consequences of a fire include the correct implementation of the Emergency Response Plan (ERP), which outlines the procedures for safely evacuating personnel from the mine and facilitating the movement of mine rescue units within the underground workings. These indicators are contingent upon the direction of the ventilation jet, its stability, and its controllability. When formulating the position of the ERP it is crucial to anticipate the parameters of fire development in terms of both time and space.

These parameters are contingent upon the fire load of the workings, the modes of spreading harmful substances and their concentrations, the impact of powerful additional energy sources on the state of the ventilation network, the utilization of fire-fighting equipment and means designed to enhance the stability of ventilation and other relevant factors. The most probable locations for the occurrence of fires are inclined mine workings equipped with belt conveyors. Given the limited data available on the processes occurring during the burning of conveyor belts in inclined mine workings, further research is required in this area. It is recommended that data obtained from measurements conducted in real conditions be combined with data from CFD modeling to gain a more comprehensive understanding of the phenomenon under investigation. This approach will permit the investigation of the influence of variable parameters that cannot be examined in the original experiments.

2. Materials and methods

The processes of airflow formation in inclined workings were studied based on inclined conveyor workings of the mining and processing plant of PJSC ArcelorMittal Kryvyi Rih. The workings consist of two parallel branches, each with a conveyor that delivers rock to the surface. The workings are connected along the length by four cross-workings. The total length of each branch is 622 meters. The height difference in the workings is 157.3 meters, with an inclination angle of 13-15°. The geometric parameters of the workings are presented in Table 2. Figure 1 illustrates the location of the workings model in space.

Table 2. Geometric parameters of the mine workings

Section number	Cross-section, m^2	Length of the mine workings, m	The angle of inclination, degrees	Altitude of the starting point, m	Altitude of the final point, m
l1	24.0	31	13.1	-85.0	-78.0
l2	18.8	31	15.0	-78.0	-70.0
l3	16.9	85	15.0	-70.0	-48.0
l4	19.4	77	15.1	-48.0	-28.0
l5	19.7	190	14.6	-28.0	20.0
l6	17.5	208	14.6	20.0	72.3
r1	24.0	31	13.1	-85.0	-78.0
r2	17.5	31	15.0	-78.0	-70.0
r3	17.5	85	15.0	-70.0	-48.0
r4	14.9	77	15.1	-48.0	-28.0
r5	17.5	190	14.6	-28.0	20.0
r6	17.5	208	14.6	20.0	72.3
p1	8.0	20	-14.5	-80.0	-85.0
p2	8.0	12	0.0	-85.0	-85.0
p3	12.0	180	0.0	-85.0	-85.0
p4	8.0	10	0.0	-70.0	-70.0
p5	8.0	10	0.0	-48.0	-48.0
p6	8.0	10	0.0	-28.0	-28.0
p7	8.0	10	0.0	20.0	20.0
v1	–	–	–	-78.0	-78.0
v2	–	–	–	-78.0	-78.0

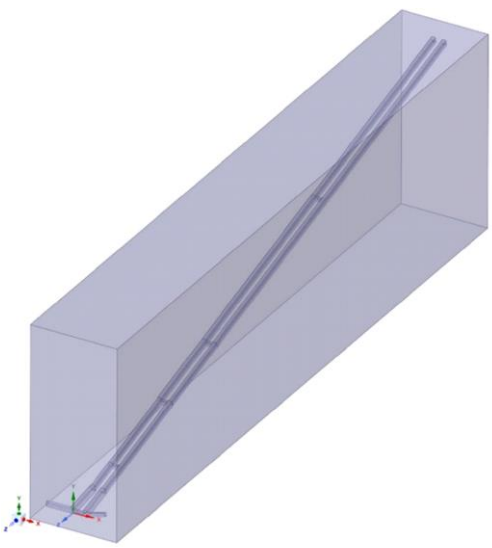

Figure 1. Location of the mine workings in space

The total volume of air in the mine is 24941.16 m³, and the total mass of air is 30552.92 kg.

A mathematical model was developed based on the geometric parameters of the workings (Fig. 2), which contains 867723 cells, 1845847 faces, and 200753 nodes. CFD calculations were conducted using the Fluent program.

To ensure that the airflow behavior in the mathematical model and in the actual working face was similar, the results of decompression measurements in each section of the working face were utilized. The airflow resistance in the mathematical model was varied by changing the wall surface parameters, namely Roughness Height and Roughness Constant.

The flow phenomena were calculated using the averaged Reynolds-Navier-Stokes equations with a k-ε turbulence model, and buoyancy was controlled by applying the Boussinesq approximation. A material with parameters close to those of the ore body was used for the walls of the workings (Table 3).

Table 3. Characteristics of the mine wall material

Parameters	Magnitude
Density, kg/m^3	3500
Cp (specific heat), J/(kg K)	808.1
Thermal conductivity, W/(m K)	2.6458

The conveyors are represented by a prism with a cross-sectional area of 2×1 m and a height of 1.2 m relative to the bottom of the working face. The conveyor belt was constructed using the material specified in Table 4, which is characterized by the parameters indicated therein.

Table 4. The physical characteristics of conveyor belts

Parameters	Magnitude
Density, kg/m^3	929.78
Cp (specific heat), J/(kg K)	1968.5
Thermal conductivity, W/(m K)	0.11018

A numerical model utilizing species transfer modeling was employed to simulate the fire. As indicated in [17], the heat released during the combustion of the conveyor belt varies between 2 and 9 MW, with the fire area reaching 20 m². In this paper, a fire with the maximum possible parameters was studied. The flame center is situated on the conveyor belt of branch r2 and has a length of 10 meters and a width of 2 meters. Heptane was employed as a flame-forming fuel at a constant flow rate of 0.01023 kg/m^2·s. Heptane was selected as the most frequently utilized fuel in experimental and fire resistance testing scenarios.

3. Results and discussion

3.1. The modeling of air exchange in the mine before the fire

The inlet and outlet flow parameters were obtained through field measurements. The outcomes of the field measurements and CFD modeling conducted before the fire are presented in Table 5. The graphs of relative pressure changes along the length of the working branches are presented in Figures 3 and 4.

The resistance of the branches of workings was selected based on actual depression values. Graphs of changes in relative pressure along the length of the workings of the CFD model and real measurements demonstrate an acceptable degree of agreement.

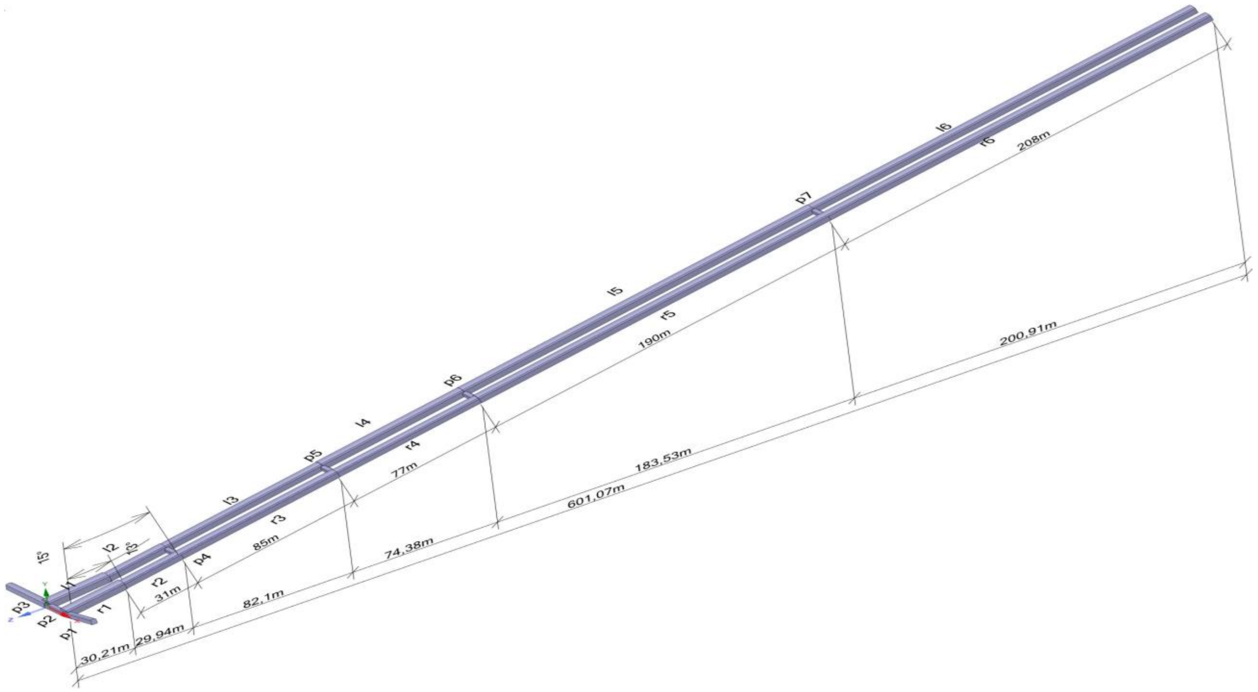

Figure 2. Geometric parameters of the mine workings

Table 5. The results of field measurements and CFD modeling conducted before the fire

Section number	Before the fire occurred					
	Measurement		Model		Measu-rement	Model
	Q_v, m^3/s	Q_m, kg/s	Q_v, m^3/s	Q_m, kg/s	V, m/s	V, m/s
p1	53.16	64.91	52.35	64.12	6.60	5.58
p2	36.10	44.08	37.77	46.27	4.10	4.03
p3	2.80	3.41	2.77	3.39	0.31	0.29
l1	34.30	41.82	35.39	43.36	1.25	1.39
r1	16.06	19.59	14.88	18.23	0.81	0.80
v1	3.81	4.65	2.80	3.43	–	–
v2	6.44	7.86	6.44	7.89	–	–
l2	31.48	38.27	32.47	39.77	1.50	1.62
r2	8.62	10.48	8.25	10.10	0.40	0.44
p4	6.15	7.48	6.03	7.39	0.78	0.87
l3	25.34	30.73	26.43	32.38	1.30	1.48
r3	14.77	17.97	8.25	17.37	1.00	0.76
p5	1.76	2.14	6.03	0.38	0.30	0.22
l4	27.09	32.81	26.19	32.08	1.30	1.25
r4	13.01	15.78	14.43	17.68	0.9	0.93
p6	3.33	4.03	6.03	3.14	0.4	0.43
l5	23.77	28.73	23.59	28.90	1.2	1.11
r5	16.34	19.77	17.08	20.93	0.9	0.92
p7	3.70	4.47	2.23	2.73	0.5	0.39
l6	20.06	24.19	21.29	26.08	1.1	1.15
r6	20.04	24.14	17.08	23.63	1.1	1.04

The distribution of air flows in the left and right branches of the working face is significantly influenced by the location in space and the airflow velocity in the lower branches p1-p3 (Fig. 5).

A high inlet velocity and a horizontal inclination of 15° result in the majority of air bypassing the right-hand branch of the workings (r1), while the high resistance of the p3 branch directs the majority of air to the left-hand branch of the workings (l1).

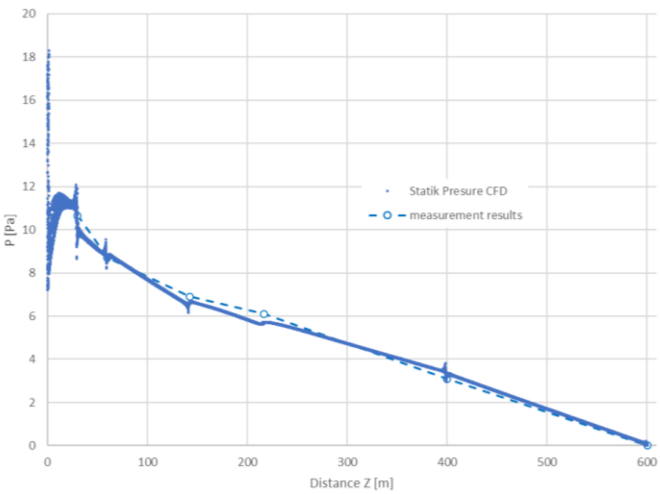

Figure 3. Pressure change along the left branch of the mine workings (measurement results and calculated values)

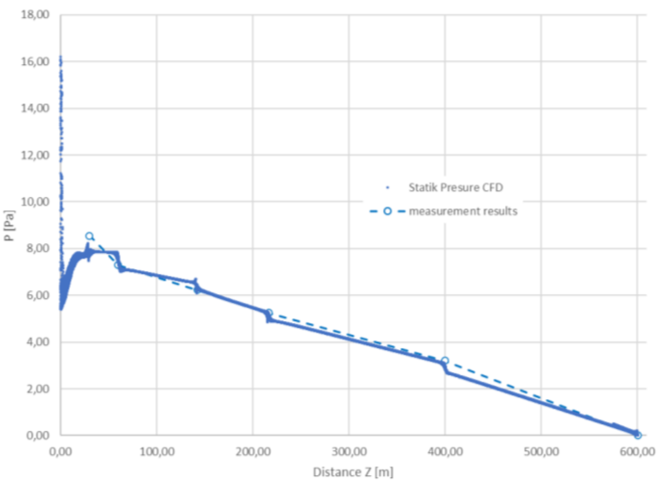

Figure 4. Distribution of air pressure along the right branch of the mine working face (measurement results and calculated values)

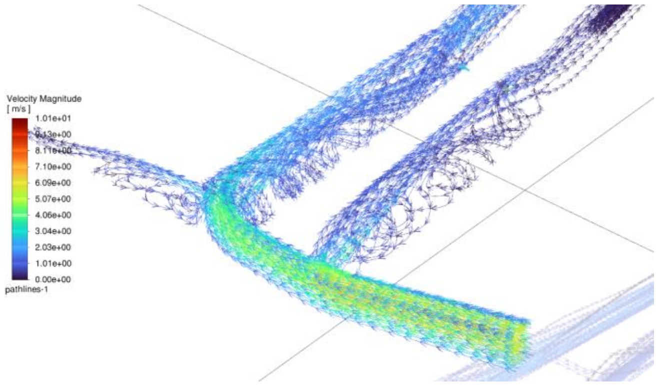

Figure 5. Airflow velocity and direction in the lower part of the mine workings

The perpendicular location of the p1 branch to the r1 and l1 branches, as well as the 13° rise of these branches, cause the air flow to spiral and significantly increases the turbulence of the flow (Fig. 6). Consequently, the elevated turbulence results in a swift reduction in the velocity of the airflow in the forward direction.

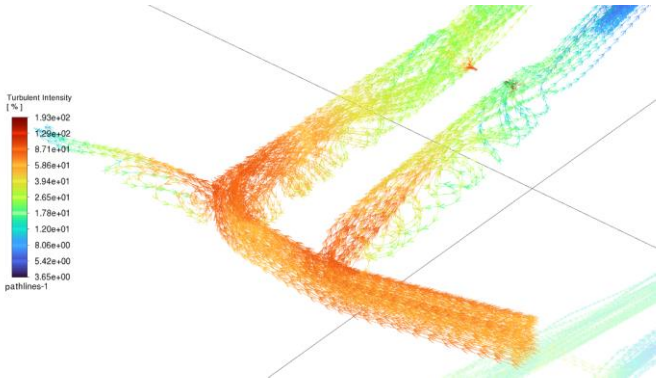

Figure 6. The intensity of turbulence in the air flows in the lower part of the mine working face

The higher air pressure in the left branch at sections l1-l6 results in a portion of the air flowing into the right branch through the cross-workings p4-p7. The velocity of the air is not uniformly distributed across the cross-section of the workings. The distribution of air is influenced by the swirling of the flow and the unevenness of the wall surface. Consequently, due to the swirling of the flow, the highest air velocities in the areas l1 and r1 are noted in the upper left corners of the workings (Fig. 7).

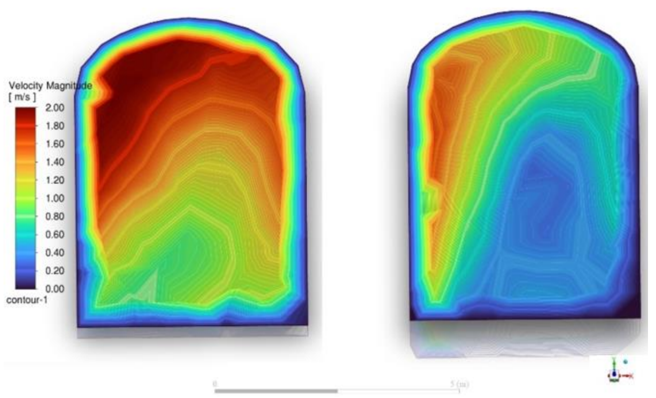

Figure 7. Distribution of air velocity along the cross-section of sections l1 and r1

Once the airflow has been stabilized, the velocity distribution over the cross-section of the working face becomes more uniform (Fig. 8).

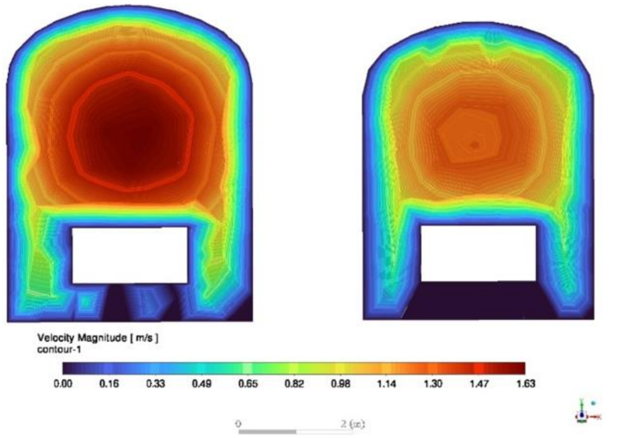

Figure 8. Distribution of air velocity along the cross-section of sections l5 and r5

Furthermore, airflow turbulence affects the uniformity of pressure distribution across the face. Consequently, the standard deviation in the pressure distribution across the cross-section of the working face in section l1 is 0.200 with an average pressure value of 11.30 Pa, while in section l4 it is 0.009 with an average pressure value of 6.17 Pa.

3.2. The air exchange modeling in a mine working in case of fire

The data obtained from the training allowed for the use of the model to simulate and analyze the movement of air masses during a fire. A fire with a heat output of 9 MW significantly altered the distribution of air flows (Table 6). During the modeling process, it was assumed that the quantity of air entering the workings through section p1, both before and during the fire, remained constant. Similarly, the quantity of air exiting through area p3 and channels v1 and v2 remains unaltered.

Table 6. CFD modeling results in case of fire

Section	During the fire				
number	Q_v, m^3/s	V, m/s	T_{avr}, °C	T_{max}, °C	$CO_{2\,AVR}$
p1	52.6	5.6	16.0	16.0	7.41E-08
p2	18.2	2.1	16.0	16.0	7.41E-08
p3	2.8	2.1	16.0	16.0	1.22E-07
l1	15.4	0.6	16.0	16.0	1.15E-07
r1	34.4	2.7	16.0	16.0	7.59E-08
v1	–	–	16.0	16.0	–
v2	–	–	16.0	16.0	–
l2	12.6	0.6	16.0	16.0	3.02E-07
r2	40.0	2.7	136.1	1991.3	9.35E-03
p4	34.5	3.9	18.9	20.7	3.00E-05
l3	21.5	1.2	20.7	20.7	5.20E-05
r3	88.8	4.8	135.4	244.6	8.28E-03
p5	13.0	3.9	20.8	21.8	5.70E-05
l4	34.6	1.7	20.7	20.8	4.78E-05
r4	102.2	6.6	116.3	157.6	6.87E-03
p6	22.6	2.7	20.5	20.7	3.64E-05
l5	57.0	2.7	20.7	21.3	4.34E-05
r5	123.9	6.7	94.7	112.7	5.32E-03
p7	22.6	2.7	42.3	68.7	1.59E-03
l6	57.0	2.7	20.0	20.0	7.74E-10
r6	126.1	6.8	92.4	97.9	5.14E-03

The fire center is situated on the surface of the conveyor belt in area r2. The combustion of gas generates airflow with a temperature of 700-1900 °C and a velocity of up to 9.1 m/s (Figs. 9 and 10). The highest temperature, 1950°C, is observed in the vicinity of the conveyor belt surface. The temperature of the roof surface of the mine workings is 510°C.

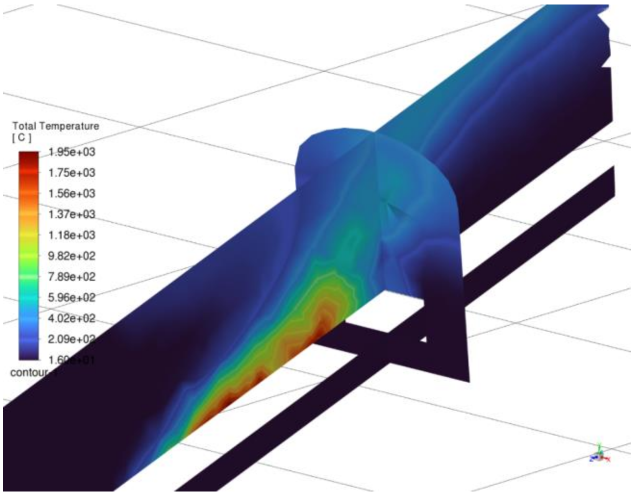

Figure 9. Gas temperature in the fire spot area

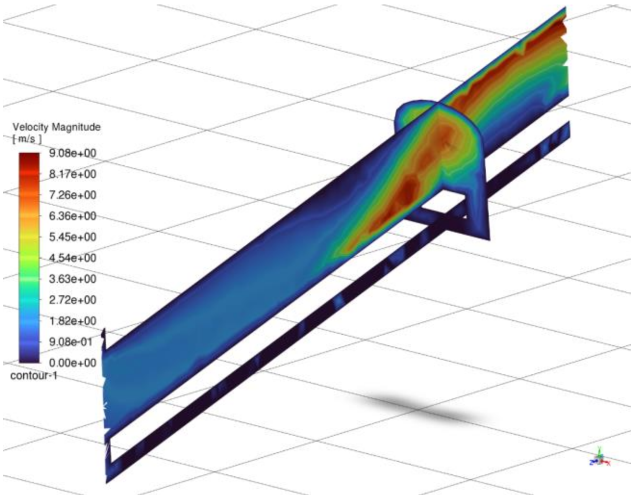

Figure 10. The gas velocity in the fire spot area

The parameters of the gas flow before and after the fire spot were studied on two surfaces (Fig. 11). The results of the research are presented in Table 7.

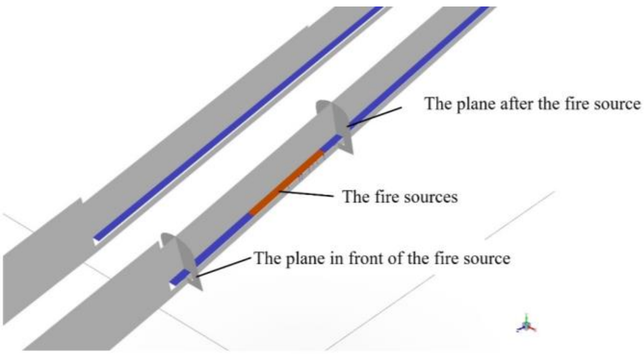

Figure 11. Location of the surfaces for studying the parameters of gas flow before and after the fire spot

Table 7. Parameters of gas flow directly before and after the fire spot

Plane	Mass flow rate, kg/s	Volumetric flow rate, m^3/s	Area-weighted average density, kg/m^3
Before-fire	26.346	21.473	1.215
After-fire	26.449	34.617	1.008

The discrepancy in gas masses before and after the fire is 0.102 kg/s, which can be attributed to the heptane flow that simulates the fire. The difference in gas volumes before and after the fire is 13.143 m^3/s. The observed increase in volume of 0.435 m^3/s can be attributed to the introduction of heptane into the system. The observed expansion of gases at high temperatures, with a volume of 12.709 m^3/s, can be considered a secondary effect. Consequently, due to thermal expansion, the volume of gases increases by 59.2%. Concurrently, the heated gas flow density decreases to 0.601 kg/m^3 (Fig. 12) in comparison to 1.215 kg/m^3 for the airflow to the fire center (Fig. 13).

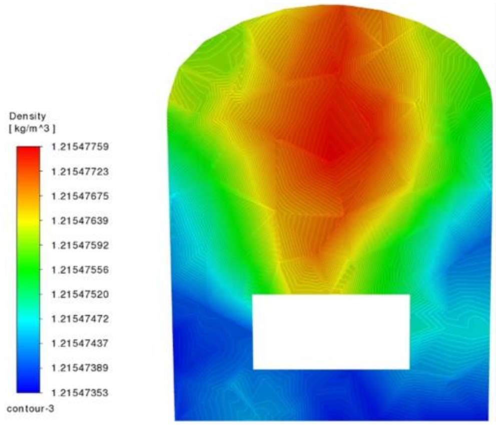

Figure 12. Air density distribution on the plane directly before the fire spot

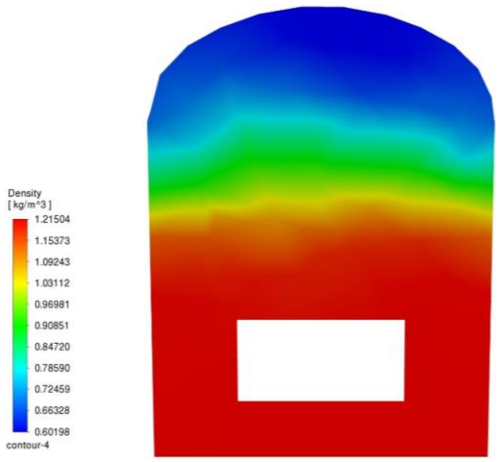

Figure 13. Distribution of gas density on the plane directly after the fire spot

The distribution of gas density within the fire center is illustrated in Figure 14. Figure 15 presents a visualization of the distribution of gas flow density in the fire zone. The thermal expansion of gases and their low density significantly impact the formation of gas flows in an inclined working face. The fire zone exhibits high turbulence (Fig. 16), which results in the mixing of air flows and a gradual decrease in the jet temperature.

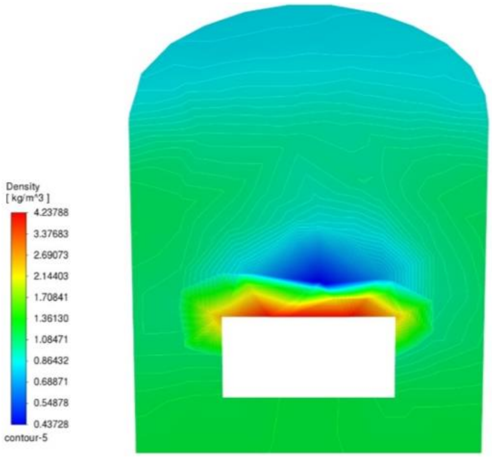

Figure 14. Distribution of gas density on the plane in the fire spot

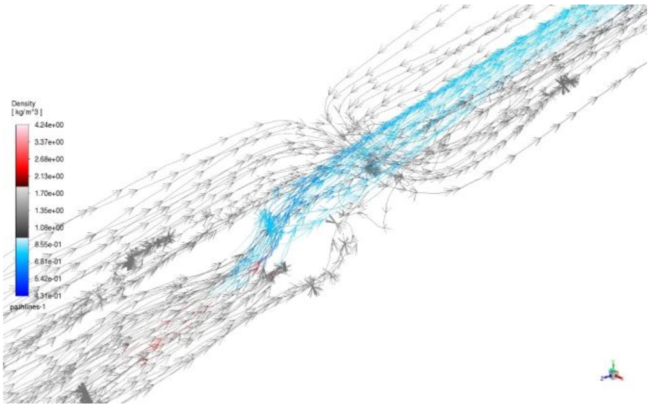

Figure 15. Changes in the density of gases in the fire zone

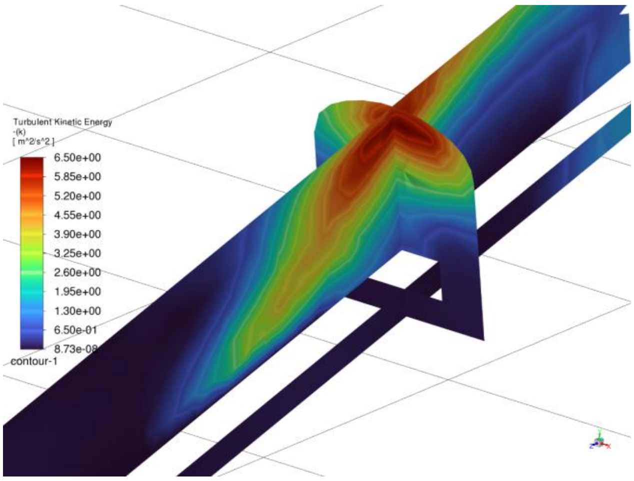

Figure 16. Turbulence energy in the fire source area

The combustion products are located close to the roof along the entire length of the working face. As the working face is approached from the end, the maximum temperature of the roof gradually decreases, reaching 95°C at the outlet (Fig. 17).

As with pressure, the jet velocity varies along the length of the working face (Fig. 18). As the jet moves away from the fire center, the jet velocity gradually increases until it reaches a value of 11 m/s in the middle of section r3. The maximum jet velocity is observed to reach its highest value, 12.4 m/s, at the beginning of section r5. At the outlet of the workings, the maximum jet velocity is 10.2 m/s.

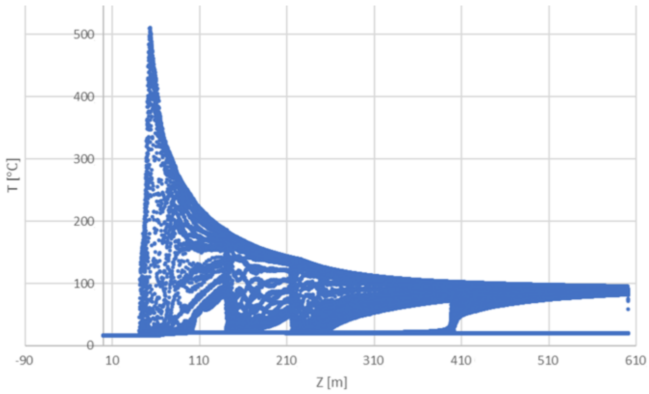

Figure 17. The temperature distribution of the working face walls along the length of the right branch

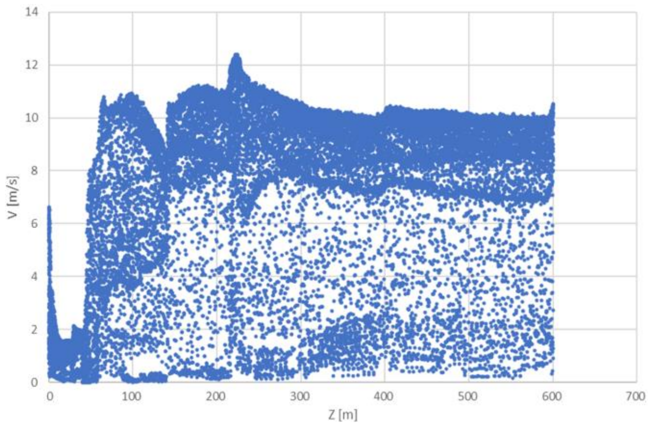

Figure 18. Air velocity distribution along the length of the right branch

The observed decline in velocity at a distance of $Z = 140$ m can be attributed to the methodology employed for the acquisition of the values. The velocity values were obtained from a conditional vertical plane that passes through the center of the workings. At a distance of $Z = 140$ m from the origin, a strong airflow from the cross-cutting face p5 enters the right branch. This incoming flow causes the main jet to deviate from the midplane, as illustrated in the graph by a decrease in velocity.

The heat flow significantly changes the pressure distribution in both the right and left branches of the workings (Fig. 19).

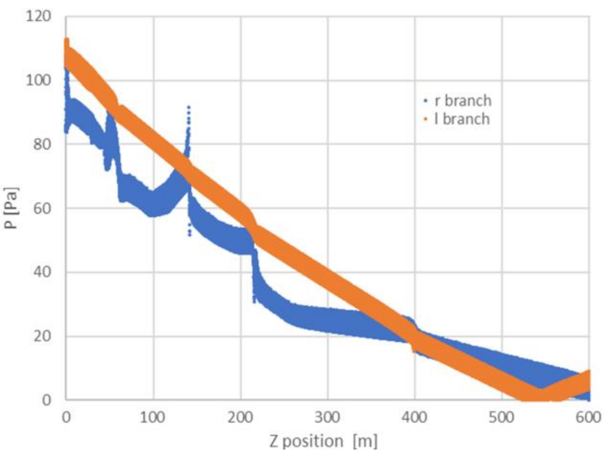

Figure 19. Pressure distribution along the right and left branches of the mine workings

The lower pressure value in the right branch results in the overturning of the airflow in sections l3-l6 and the supply of air to the right branch through the cross-workings p4-p7. The left branch draws air through the upper outlet of the working face, thereby creating a pressure of -6.92 Pa at the cut. Concurrently, the mass of the air being drawn is 72.1 kg/s. This air feeds the right branch through the transverse workings p5-p7 and partially through p4 (Table 8). Concurrently, the mass of air exiting the right branch has a five-fold increase in comparison to the state before the fire.

Table 8. Airflow from the left branch to the right branch through the cross-cutting workings

Section number	Air source	Mass of air transferred from the left branch to the right branch, kg/s
p4	l2	14.47
p4	l3	25.30
p5	l4	16.06
p6	l5	27.01
p7	l6	3.29

The overturning of the jet in the left branch of the workings has resulted in the distribution of combustion products solely within the right branch. The mass fraction of CO_2 in the air decreases from 0.018 in the fire zone to 0.005 at the outlet of the right branch as it approaches the exit of the workings. Concurrently, due to the elevated temperature, carbon dioxide in the lower sections is located in the upper part of the workings. In the fire zone, its mass fraction reaches 0.037, and as it approaches the exit from the right branch, it is distributed throughout the entire cross-section (Figs. 20, 21).

The mass fractions of CO_2 changing along the length of the right branch of the working are illustrated in Figure 22.

The quantity of oxygen present in the air supplied to the combustion chamber is sufficient for the combustion reaction to complete. Consequently, the reduction in the oxygen content of the gas in the vicinity of the combustion center is observed only in this area (Fig. 23). Surface integration data along the planes perpendicular to the axis of the working face reveals that the mass of oxygen passing through the working face is 6.02 kg/s immediately before the fire spot and 5.69 kg/s immediately after the fire spot.

The elevated temperature of the combustion products (Fig. 9) and the surplus of oxygen significantly diminish the probability of carbon monoxide (CO) formation, given that the self-ignition temperature of CO is 644°C.

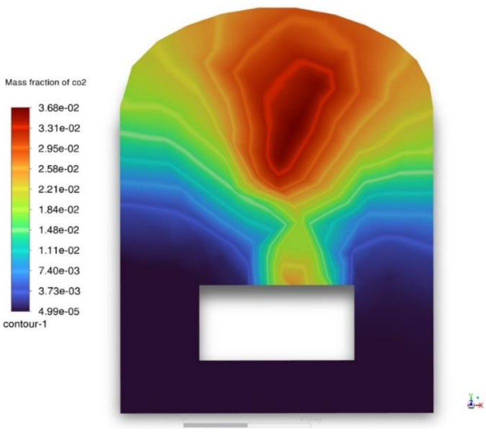

Figure 20. The CO_2 distribution along the cross-section of the working face in the fire zone

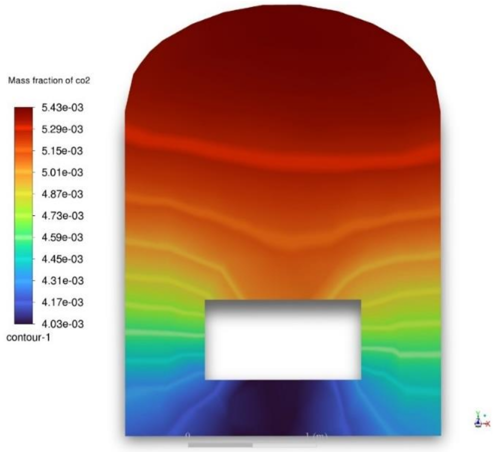

Figure 21. The CO_2 distribution along the cross-section of the working face in the upper part of the right branch of the working face (r6)

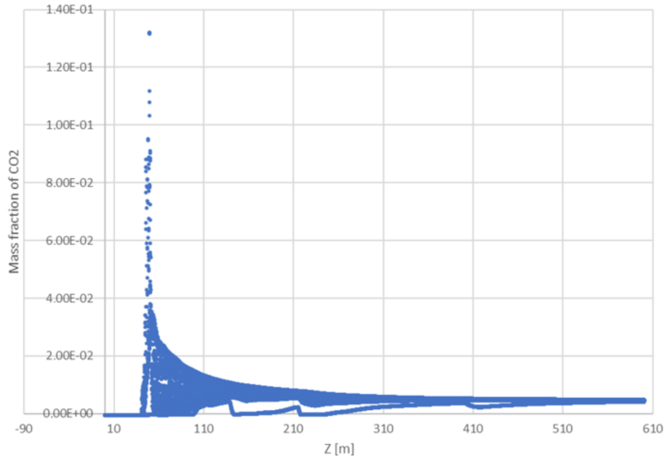

Figure 22. The mass fraction of CO_2 changing along the length of the right-hand branch

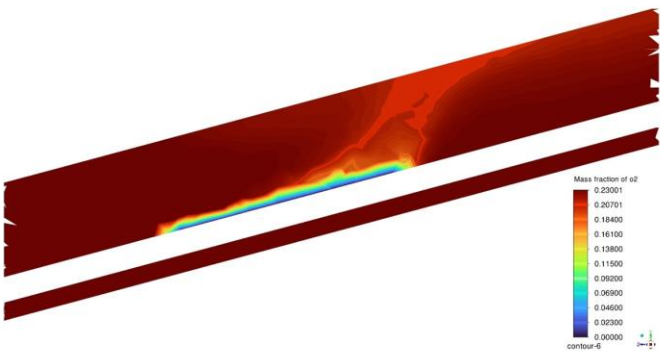

Figure 23. The fraction of O_2 mass fraction in the fire zone

Previous studies of conveyor belt fires have focused on horizontal workings or workings with a small angle of inclination. In such workings, the gravity component has very little effect on the formation and distribution of air flows.

The mathematical model shows that the gravitational component has a significant effect on fires in workings with a large angle of inclination. Due to the influence of gravity, a decrease in the density of the mixture of hot air and combustion products leads to a significant increase in their velocity, which in turn changes the distribution of the total pressure in adjacent workings. The difference in pressure in adjacent workings affects the volume and direction of air movement in the cross-ducts and overturning of the air flow.

In further studies it is necessary to analyze the influence of such factors as the angle of inclination of the mine workings, aerodynamic resistance of the mine working elements and fire power on the formation and distribution of air flows. The results of such studies would make it possible to develop mathematical dependencies of the influence of these factors on the formation and distribution of air flows during the burning of a conveyor belt in inclined workings, which would significantly increase the reliability of identifying the most dangerous areas for fire and planning the most rational actions to extinguish the fire in specific unique conditions.

4. Conclusions

The paper presents the results of practical measurements of airflow distribution in an inclined conveyor operating at the mining and processing plant of PJSC ArcelorMittal Kryvyi Rih. The obtained data allowed creating and calibrating a mathematical model of the plant. Based on the obtained data, a mathematical model was created, which was then used to perform CFD modeling of gas flows in the mine under normal conditions and under conditions of a fire with a thermal capacity of 9 MW.

A 9 MW fire significantly changes the distribution of air flows. Thermal expansion causes the volume of gases behind the fire to increase by 59.2%. In an inclined mine, the thermal expansion of gases and their low density have a significant effect on the formation of gas flows. As the jet moves away from the center of the fire, the jet velocity gradually increases. The maximum jet velocity is reached at the beginning of section r5, where it reaches 12.4 m/s.

The left branch sucks air through the upper outlet of the mine, creating a vacuum of -6.92 Pa. As a result of this supply, the mass of air coming out of the right branch has a fivefold increase compared to the pre-fire condition.

The overturning of the jet from the left branch of the plant leads to the distribution of the combustion products exclusively along the right branch. Due to the higher temperature in the lower parts of the mine, carbon dioxide is located in the upper part of the mine. Its mass fraction in the fire zone reaches 0.037, and as it approaches the exit of the right branch, it is distributed throughout the entire cross-section.

The high temperature of the combustion products and excess oxygen significantly reduce the probability of carbon monoxide (CO) formation.

Author contributions

Conceptualization: DB; Data curation: RM; Formal analysis: RM, SS; Funding acquisition: DB; Investigation: RM, SS, LY; Methodology: RM, LY, OP; Project administration: DB; Resources: OP; Software: SS; Supervision: DB; Validation: RM, OP; Visualization: SS; Writing – original draft: RM, SS, LY; Writing – review & editing: DB, RM, SS. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Моделювання стійкості повітряних потоків у похилих виробках під час пожежі

Д. Бровко, Р. Макарейко, С. Сахно, Л. Янова, О. Пищикова

Мета. Визначення механізму розподілу повітряних потоків та дослідження процесів, які відбуваються під час пожеж конвеєрних стрічок у похилих виробках шляхом розробки математичної моделі.

Методика. Проведені практичні вимірювання розподілу повітряних потоків у похилому конвеєрі, що експлуатується на гірничо-збагачувальному комбінаті ПАТ "АрселорМіттал Кривий Ріг". На основі отриманих даних була створена математична модель, яка потім була використана для виконання комп'ютерного гідрогазодинамічного (CFD) моделювання газових потоків в шахті при нормальних умовах і в разі пожежі тепловою потужністю 9 МВт.

Результати. Виявлено особливості поведінки газових потоків під час горіння конвеєрної стрічки в похилих виробках та вплив турбулентності потоку, зміни густини газів при нагріванні та гравітаційних ефектів на розподіл газів у поперечному перерізі й по довжині виробки. Осередок пожежі з тепловою потужністю 9 МВт значно змінює розподіл повітряних потоків. Теплове розширення викликає збільшення об'єму газів на 59.2% за вогнищем пожежі. Теплове розширення газів та їх низька густина мають значний вплив на формування газових потоків у похилій виробці. У міру віддалення від центру пожежі швидкість струменя поступово зростає і досягає значення 12.4 м/с. Це веде до суттєвої зміни розподілення загального тиску в суміжних виробках та збільшення турбулентності потоку. Внаслідок цього маса повітря, що виходить з правої гілки, збільшується в п'ять разів у порівнянні зі станом, що існував до пожежі. Перекидання струменя з лівої гілки виробки призводить до розподілу продуктів горіння виключно по правій гілці.

Наукова новизна. Дослідження допомогло зрозуміти механізм перекидання струменя та особливості розповсюдження продуктів горіння при пожежі в похилих конвеєрних виробках.

Практична значимість. Результати досліджень дозволяють спрогнозувати ймовірність виникнення пожежі, виявити найбільш небезпечні для загоряння ділянки та спланувати найбільш раціональні дії для гасіння пожежі в конкретних унікальних умовах.

Ключові слова: *підземна пожежа, гірнича безпека, вентиляційна мережа, видобуток корисних копалин, обчислювальна гідродинаміка*

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