RGNZ/MGPB

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 622.81
DOI: 10.17794/rgn.2023.2.10

Original scientific paper

Mechanism of coal aerosol explosion development in an experimental mine working

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Abstract

Today there is not enough scientific data on the energy level and the velocity of an explosion in actual mine workings, which have a cross-sectional area larger than experimental mine workings. The objective of the paper is to justify the energy parameters of an explosion in actual mine workings based on the disclosure of the fire front development mechanism when coal dust explodes in an experimental mine working with a limited cross-sectional area. These studies can be the basis for choosing the speed of action and the strength of the means of the localization of dust explosions. The main research method is an experimental and analytical method, based on the analysis of the results of experimental explosions of coal dust in experimental mine workings and theoretical substantiation of the regularities of the development of the velocity and additional energy of the fire front with further extrapolation to the conditions of actual mine workings. It is proposed to supplement the mechanism of explosion development with an idea about the sections of development of explosion dynamics, i.e. initiation, dust explosion, crater, which determine the characteristic parameters of the explosive front velocity: maximum initiating velocity, average velocity, and maximum velocity in a crater. It was established that during methane initiation in the experimental mine working at the boundary between the initiation and dusting zones, there is a situation of a hybrid explosion of a mixture of methane and dust with air, which has its own velocity and energy indicators. A linear dependence of the energy generated during the coal aerosol explosion on the cross-sectional plane of the mine working was established. This makes it possible to use the results of testing the coal from certain deposits in small-scale experimental set-ups to justify the parameters of protective means for the actual mine workings.

Keywords:
mine workings; coal aerosol; coal dust explosion; explosive front velocity

1. Introduction

Explosions in mine workings involving coal dust are characterized by the highest mortality rate in the coal mining industry. Analysis of accidents in the coal mines of Ukraine over the past decades showed that explosions of methane-air and hybrid dust-air mixtures are very common (**Zavialova et al., 2021, Kostenko et al., 2022**). As a result of these accidents, 1,349 miners were injured, 732 of them were fatally injured. Despite the fact that it became possible to reduce their frequency in the 21st century, these accidents have extremely serious consequences. In just six months there were explosions in Poland (April 2022). The progress of rescue work in such emergencies is quite time-consuming, and takes place under conditions of the threat or immediate occurrence of repeated explosions. The problem of improving knowledge about the mechanism of the occurrence and development of the explosion of air mixture with methane and coal dust remains relevant. Currently, it is necessary to develop complex solutions in order to prevent explosions, as well as for the containment and minimization of injuries when they occur. The existing methods and means of prevention and localization of explosions do not provide reliable protection and need improvement.

2. Analysis of recent research and publications

The study of the conditions for the occurrence and development of explosions of gas and air mixtures and

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coal aerosols is carried out by means of theoretical modelling, including computer modelling, laboratory and empirical studies, as well as conducting research in the experimental mine workings in the conditions brought to the actual ones as much as possible.

The dynamics of the development of explosive coal aerosol caused by seismic waves was analyzed by means of computer modelling for the workings with an initial safe content of methane and dust in the air (**Kostenko et al., 2022**). It was justified for the first time that seismic waves from methane explosions occurring in the rock mass can lead to the rise of dust deposits from the walls of the mine working into the air. This is because the velocity of seismic waves in the rocks is higher than the velocity of the propagation of the explosive front in the air environment of the mine working.

The study of the effect of the particle-size distribution of coal dust on its tendency to explode is ongoing. The effect of the size of coal dust particles on their burning rate in a closed chamber was studied. From three different mines, coal dust with particle sizes of 149, 125, 105, 74, 63, 53, 44, 37 μm was selected for explosion tests in a closed chamber with a volume of two litres (**Moradi et al., 2019**). All tests were carried out at a pressure of 1.5 bar and an initial temperature of 25°C. It was established that particles of coal dust with sizes of 44 μm and 37 μm have a higher burning rate when compared to other sizes.

With the help of an explosive combustion chamber designed as a sphere with a volume of 20 litres (**Rodionov et al., 2018**), it is shown that the particle-size distribution of coal dust affects the explosion pressure, the rate of increase of the explosion pressure and the transformation ratio. It was proven that dust with a fractional size distribution of 63-94 μm has the most explosive properties. Two maxima of the explosion pressure growth rate are observed, one of which occurs at a concentration of 100 g/m^3, and the second – at 400 g/m^3. The analysis of experimental data confirmed that in the development of fire retardants and fire extinguishing agents used in the automatic means of explosion containment, it is necessary to conduct further studies for the coal dust fraction with a particle-size distribution of 63 to 94 μm.

The means of studying the explosiveness of coal dust are being elaborated, with a new 38-litre chamber for testing explosions of coal dust created (**Eades et al., 2019**). The chamber has design modifications to simulate the unique conditions in an underground coal mine. A series of explosive tests was conducted using a sample of Pittsburgh coal dust and a 5 kJ igniter. For each test, an analysis was carried out in order to determine the maximum pressure ratio and the dust flammability parameter. The results of the analysis were used to assess the tendency to transfer the explosion or its absence for each concentration.

A unique equipment with a volume of 40 L was created to study the conditions of the detonation of gas and dust mixtures from the endogenous sources of the heating of coal piles (**Wang et al., 2021**). It was used to study the characteristics of the explosion of methane and coal dust when ignited by a high-temperature surface heat source. The three parameters of methane and coal dust explosion (explosion pressure, pressure rise rate, and explosion temperature) are consistent with the law of methane concentration change, i.e. the parameters first increase with an increase in methane concentration, reach a peak, and then decrease with an increase in methane concentration. Due to the addition of coal dust, the limit concentrations of the three explosion parameters of methane and air decrease from 11.5% to 9.5%, from 10.5% to 9.5%, respectively, and the peak values increase by 6.9% and 0.8%, respectively. The law of change in the explosion temperature after the detonation of methane and coal dust on the surface of a high-temperature heat source remains the same as before the addition of coal dust. The function of predicting the ignition temperature of coal dust from a high-temperature surface heat source was obtained.

Polish researchers conducted experimental studies of the deposition of coal dust in mine workings (**Prostański, 2015**). Based on the analysis of data obtained during mine tests in lava, the empirical models that describe the relationship between changes in dust concentration and dust deposition in the protective zone of mine workings were developed. The developed empirical models showed the possibility of predicting explosive dust deposits in the mine workings.

Large-scale dust explosion tests in an experimental mine were conducted by the American researchers (**Romanchenko et al., 2018**). The gallery was about 488 m long, 2.1 m high and 6 m wide. The tests began with the ignition of a methane and air mixture, the so-called ignition. To this end, a 12-meter section of the gallery, starting from the face or enclosed end, was filled with a mixture of 10% methane and air, approximately 15 m^3. A plastic membrane was used to contain the combustible gas mixture in the initiation zone before ignition. Ignition of the methane and air mixture alone caused the flame to spread approximately 70 m from the face.

The amount of coal dust in the dust zone corresponded to the rated dustiness of 200 g/m^3. Half of the mixture of coal and limestone rock dust deposited on shelves under the roof, and the rest deposited on the ground, for 91 m (i.e. at a distance of 12 to 104 m from the bottom).

This research provided some data on the depth of dust removal in the early stages of explosion development, essential to identifying potential dust explosion hazards. The hazard is posed if the actual thickness of the deposited dust layer is much greater than 25 mm, and the content of non-combustible substances on the surface of the dust deposit is less than 80%.

Technical and technological solutions in the field of dust safety of mines are presented (**Harris et al., 2019**). Central pneumatic transportation systems, which provide for the initial delivery of significant volumes of inert dust to the surface complex of the mine, storage of up to 150 tons, and daily silting with inert dust consumption of 40 to 80 tons/day and more, are proposed. The increase in the average consumption rate of inert dust from 2.6 kg/m to 28.9 kg/m is substantiated.

A number of experiments on the explosiveness of coal and limestone dust mixtures were conducted at the Lake Lynn experimental mine (**Man et al., 2009**). They were conducted in a single gallery about 1,600 feet (488 m) long, initiated by explosions of methane gas. Dust samples were analyzed in the laboratory using thermogravimetric analysis and solubility test to determine how limestone rock dust behaves when coal and rock dust explodes. The chemical composition of limestone has been found to play a certain role in its ability to inhibit coal dust explosions.

The physical and chemical properties of both coal dust and rock dust from Indian deposits were studied (**Devi et al., 2017**). All experiments were performed in the laboratory using a Godbert-Greenwald furnace with a volume of 0.234 L. The results showed that about 72% of rock dust is required to convert coal dust smaller than 212 μm into non-explosive dust. This finding also supports the 70% rock dust requirement set for Indian coal mines. However, the requirement for rock dust can reach 87% depending on the concentration of coal dust and the size of the rock dust particles.

The results obtained during explosions in the experimental mine workings remain the most representative ones. The experimental base of active research centres for conducting full-scale coal dust explosions is reviewed; the test methods and conditions for conducting coal dust explosions are presented (**Romanchenko et al., 2022**). The main factors determining the dynamics of the shock explosion wave and the explosion flame front are summarized. The results of an experimental study of strong and weak explosions of coal dust are presented, and their thermodynamic parameters are summarized. Based on a comparison of experimental data obtained in two currently operating research centres, the requirements for conducting tests of methods and means of ensuring dust explosion safety of mines, as well as criteria for the effectiveness of means of preventing and containing explosions, are outlined.

Summarizing the review of current information sources, it can be stated that the main factors that significantly affect the dynamics of coal dust explosions include the power of the initial charge, the length of the dust zone, the nature of the deposition of dust along the cross-section (in the roof, on the ground), as well as the amount of dust concentration, its ash content and particle-size distribution. Nevertheless, until now, there is no scientific data on the energy level and the velocity of explosions in actual mine workings, which have a cross-sectional area larger than experimental mine workings, where it is generally 3 to 7.5 m^2. This makes it difficult to justify technical parameters of the means of containment of explosions such as the speed of operation and strength for the actual mine conditions. There are not enough publications dedicated to the study of hybrid explosions, a mixture of air with methane and coal dust.

3. Objective of the paper and research methods

The objective of the paper is to justify the energy parameters of an explosion in actual mine workings as a basis for choosing the speed of operation and strength of means for the containment of dust explosions based on the disclosure of the mechanism of fire front development when coal dust explodes in an experimental mine working with a limited cross-sectional area.

The main research method is experimental and analytical method, based on the analysis of the results of experimental explosions of coal dust in experimental mine workings and theoretical substantiation of the regularities of the development of the velocity and additional energy of the fire front with further extrapolation to the conditions of actual mine workings.

4. Research results

Based on data from literature sources (**Romanchenko et al., 2022; Cybulski, 1973**), and summarizing the results given there, it is possible to make the following generalized picture of the explosion development process in an experimental mine working (see **Figure 1**). The main indicator of the characteristics of the propaga-

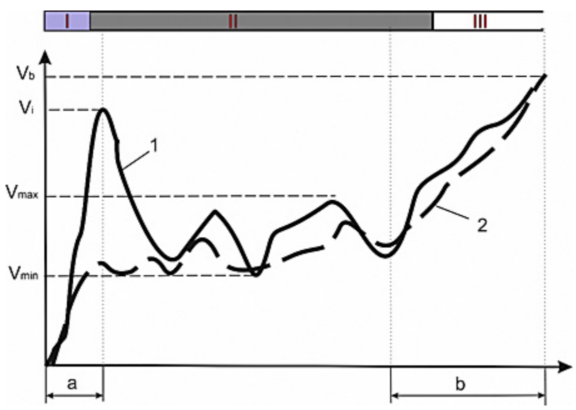

Figure 1: Scheme of the experimental mine working and plots of velocity of transfer of the coal aerosol explosion front along the mine working. I, II, III – mine working arrangement equipment zones, respectively: initial, dusty, free; a, b – areas of explosion acceleration during initiation and in the crater of the mine working; Vi, Vmax, Vmin, Vb – velocities of the explosion front, respectively: maximum initiating velocity, largest and smallest velocities when the dust explodes, maximum velocity in the crater; 1, 2 – plots of explosion velocities with powerful (initiation by gas mixture) and weak (initiation by explosives) initial charges, respectively.

tion of a coal aerosol explosion in an experimental mine working established experimentally is the velocity (V) of movement of the pressure or fire fronts along the mine working.

Three zones are usually arranged when preparing an experimental mine working for an explosion. The initiation zone *(I)* must be arranged in the experimental mine working where conditions are created for such a level of detonation of the explosive substance to ensure further transfer of the dust explosion along the mine working. Most often, this requires to filling of a part of the mine working volume with a combustible gas mixture, e.g. a mixture of methane with air, which is then detonated with a powder charge or otherwise. In addition, highly explosive coal dust deposited in a certain area of the mine working is used in the initial charge. Thus, the most powerful initial charge of the type 30 m PII (**Cybulski, 1973**), which was a 30-meter section of the strike treated with such dust, was the most powerful during research at the Barbara Mine (Poland). In some cases, when studying very explosive types of dust, zone *(I)* is absent; only the powder charge in the mortar is used as the initial charge.

The studied coal dust of different particle-size distribution is used in the next mine working zone *(II)*, which is deposited in the specified amount along the perimeter of the structure or in trays. After initiation, a coal aerosol develops in this part of the mine working, where the explosion is either transferred further or extinguished.

Zone *(III)* of the experimental mine working can be free of a combustible load, where the explosive gaseous and solid products move by inertia.

The disclosure of the mechanism of development of an explosive wave in all sections of the experimental mine working and the extrapolation of the details of this mechanism to the conditions of actual explosions in the network of coal mine workings is of particular interest. As a basis, a fairly representative and widely published sample of the results of studies of coal dust explosions at the Barbara Mine was reviewed (**Cybulski, 1973**). The advantage of these data is that they are obtained using the same experimental and measurement base, and they can be compared.

Let us consider the process of development of the velocity of the explosion front in different sections of the experimental mine working in more detail.

After detonation of the powder charge at the end of the mine working, the initiating mixture ignites; the flame quickly converts from the deflagration (slow) mode to the detonation mode of combustion. Thus, a fire starts to move from the end of the mine working, and then a shock front develops, the velocity of which (V) increases as the initial charge burns, and new volumes of hot explosion products emerge.

Depending on the type of the initial charge, two visual scenarios of the development of velocity of the explosion front are observed in the experimental mine working, namely with the development of a slope on the borders of zones I and II (see **Figure 1**, curve 1) and without a slope (curve 2).

In all cases of using the methane initial charge, the velocity of the explosion front increases from zero to a certain value V_i. On the plot (**Figure 1**, curve 1), the maximum velocity V_i looks like a slope, the section (*a*) of the acceleration of the explosive front exceeds the size of zone (*I*). Peak, the location of the top of the slope, is outside zone (*I*), in zone (*II*). The level of V_i is determined by the mass of methane deposited during the experiment set-up. The energy of the gas mixture (E_a) developed during the combustion of a combustible medium can be estimated based on the specific heat of fuel combustion, a physical quantity that shows how much heat is released during complete fuel combustion weighing one kilogram:

$$E_a = m_{CH_4} q_{CH_4} \quad (1)$$

where: m_{CH4} – mass of methane reacted in zone (*I*), kg; q_{CH4} =50,1 – specific heat of combustion of methane, MJ/kg.

In the process of initiation, methane from zone (*I*) is displaced to a certain part of section (*II*) (**Romanchenko et al., 2018**). In these conditions, there is a mixture of methane, coal dust and air in the section (*a-I*) during an explosion, i.e. a hybrid explosion occurs. The additional energy E_d, which develops in the diffusion region (*a-I*) is significantly greater than the energy in zone (*I*):

$$E_d = m_{ci} q_c + m_{CH_4 i} q_{CH_4} \quad (2)$$

where: m_{ci}, m_{CH4} – masses of coal and methane, respectively, in the diffusion region, kg; q_c=29,3; q_{CH4}=50,1 – specific heats of combustion of coal and methane, MJ/kg.

It follows from the above that the increase in energy level leads to the development of an additional amount of gases during the combustion of fuel and a further increase in their volume during the release of additional heat. This in turn leads to the increase in the velocity of the explosion front. It reaches the value V_i, sufficient for the further development of explosive processes in mine working zone (*II*), which contains coal dust and air.

When coal dust deposited in zone (*I*) is used as the initial charge or without the initial charge (see **Table 1**, explosion 1931), the slope is absent (see **Figure 1**, curve 2). These explosions are marked in colour in **Table 1**. The initiation energy is determined only by the combustion of mass of carbon m_{cc} deposited in initiation zone (*I*):

$$E_a = m_{cc} q_c \quad (3)$$

In this case, the size of the explosion acceleration area coincides with the size of zone (*I*), and sometimes it can be smaller.

Exceptions are explosions Nos. 3553, 3605, 3620, when powerful 30 m PII initial charge was used, which created velocity V_i greater than that resulting from the subsequent detonation burning of the studied dust.

Table 1: Certain indicators of coal dust explosions in the experimental workings of the Barbara Mine (**Cybulski, 1973**)

Explosion No.	Type of initial charge	Section size, m					Velocity, m/s		
		I	II	III	a	b	V_i	V_{min}-V_{max}	V_b
565	30 m PII	30	370	-	-	120		80-160	240
558	30 m PII	30	370	-	-	-	-	40-120	-
2249	50 m³ CH_4	15	185	-	20	50	960	160-420	1050
680	27.5 m³ CH_4	10	100	90	10	140	360	200-350	2000
3533	30 m PII	30	120	50	-	50	-	120-290	160
1784	50 m³ CH_4	10	180	10	20	-	560	190-680	400
3620	30 m PII	30	150	20	50	50	560	200-720	980
1931	wprost	-	100	100	-	120	-	120-600	1320
2030	50 m³ CH_4	10	150	40	20	50	600	80-160	440
2011	4 m PII	4	96	100	-	100	-	40-100	600
2010	4 m PII	4	96	100	-	100	-	40-160	1040
3605	30 m PII	30	150	20	50	40	540	80-150	280
3553	30 m PII	30	150	20	50	80	530	90-400	700
3574	50 m³ CH_4	15	155	30	15	100	760	210-590	880
2217	50 m³ CH_4	15	150	35	15	50	520	240-400	820
839	100 m³ CH_4	10	310	80	20	-	320	80-180	120
278	100 m³ CH_4	10	310	80	20	100	320	180-640	880
3406	50 m³ CH_4	15	155	30	30	30	320	90-100	200

In zone (*II*) of the experimental mine working, the conditions and the nature of the explosion propagation are qualitatively similar to those in actual mine workings. The velocity of propagation of the explosion front has a wave-like character, with the velocities in the range of V_{min}-V_{max} (see **Figure 1**).

Zone (*III*) of the experimental mine working is not charged with combustible materials, and there the fire front extinguishes. Its inhibiting effect on the velocity of the shock front decreases, while the frequency of velocity fluctuations decreases. The hot products of the explosion, accumulated in the entire mine working, move by inertia. The velocity of gases, as a rule, increases to V_g at the final section because the aerodynamic resistance of the shock front decreases sharply. Gas dynamics is similar to what happens in a cannon crater.

The inhibiting effect of the fire front is confirmed by the results of explosions Nos. 558, 839, 1784, where there was no free zone (*III*). In the final section, the velocity of the explosive front did not increase, but remained within the range of V_{min}-V_{max}.

The conducted analysis allows us to state that when using experimental data to justify the parameters' speed of operation of technical means designed to contain coal aerosol combustion fronts moving through underground mine workings, one should take into account the peculiarities of the development of explosions in the experimental set-ups. It makes sense to focus on velocity indicators V_i when a hybrid mixture of methane and aerosol burns. In the absence of methane, an indicator not lower than V_{max} should be considered.

As mentioned before, the experimental mine workings have a small cross-sectional area *S* compared to the actual mine workings. Such indicators for modern coal mine workings are more than $S=9\ m^2$, and $S\geq 20\ m^2$ for ventilated mines with a high production load.

The total energy of gases E_d, concentrated in the cross-section of the mine working, can be calculated as the sum of kinetic energy E_k, internal energy E_v, and energy of chemical transformation of combustible components E_h.

For clarity and convenience, we recommend to consider the relative energy E_d, concentrated on a section of the mine working with a length of 1 meter (L=1 *m*). It can be calculated from the following expression:

$$E_d = m_i\left(\frac{V_i^2}{2} + \frac{kR}{M_i}T_p\right) + m_c q_c + m_{CH_4} q_{CH_4} \quad (4)$$

where:

- m_i, m_c, m_{CH4} – mass of air, coal dust and methane, respectively, *kg*;
- k – coefficient, k= 5/2 for diatomic (O_2, N_2, H_2, CO) and k =3 for polyatomic (CH_4, CO_2, H_2O, C_2H_2, etc.) gases;
- R – universal gas constant, R = 8.3145, *J/(mol K)*;
- M_i – gas molar mass, *kg/mol;*
- T_p – air temperature, *K;*
- V_i – velocity of the gas flow in the given section, *m/s*.

Considering that the total mass of coal dust and methane, which are in the analyzed volume, is significantly less than the mass of the rest of the air, and the energy of

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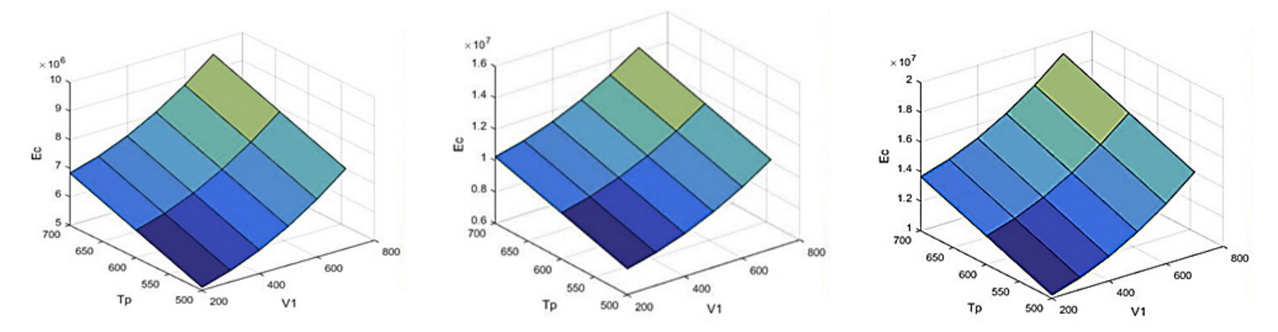

Figure 2: The amount of energy (E_s, J) developed during the explosion of coal aerosol at the cross-sectional area of the mine working (m^2). *Fragments *a, b, c* provide equality of geometric scales of the initial and final values.

their transformation is mainly implemented in the form of heat and volume of gases, we assume, as a first approximation, that the last two members of the expression (4) can be neglected. Based on this, the dynamic impact on the protective structure is mainly exerted by kinetic energy E_c in the form of a shock wave of explosive gases flow moving at a certain velocity and changing density when heated:

$$E_c = m_i\left(\frac{V_i^2}{2} + \frac{kR}{M_i}T_p\right) \quad (5)$$

In this expression, with the size of the cross-sectional area S per unit of length (L=1 m), the air mass is:

$$m_i = S \cdot L \cdot \rho \quad (6)$$

where ρ – air density under normal conditions, kg/m^3;

The type of expression (5) indicates a linear dependence of energy on the mass of air in the mine working cross-section. The larger is the cross-sectional area, the greater the kinetic energy developed during the explosion of coal dust that can affect the protective explosion retardant.

For a quantitative comparison of the impact of the size of the mine working cross-section, the calculation of the kinetic energy developed during the explosion in the mine workings with an area of 10; 15; 20 m^2. The following temperature ranges of explosive gases are used for the calculation: K, $500 \leq Tp \leq 700$, and their velocities, m/s: $200 \leq V_i \leq 800$ (see **Figure 2**).

As evidenced by the results of the calculations, with an increase in the cross-sectional area of the mine working, an increase in the energy of the explosive front is observed. Thus, the maximum indicator E_s at T_p=700, K and V_i=800, m/s was about $1 \cdot 10^7$, $1{,}5 \cdot 10^7$, $1{,}9 \cdot 10^7$ J at S 10; 15; 20 m^2 respectively (see **Figure 2**). A clear linear dependence of the growth of the energy value on the increase in temperature is observed. Thus, at S=20 m^2 and V_i=200 m/s an increase in gas temperature by 200 K (from 500 to 700) provides an increase in energy from $1 \cdot 10^7$ to $1.35 \cdot 10^7$ J (see **Figure 2c**).

A parabolic dependence of energy growth with an increase in flow velocity V_i is observed. Thus, in the mine working with S = 15 m^2, at T_p=500 K, after a velocity increase V_i from 200 to 800 m/s, energy increased from $0.7 \cdot 10^7$ to $1.2 \cdot 10^7$ J (see **Figure 2b**).

5. Discussion of research results

The research results presented in this paper are aimed at revealing the mechanism of coal aerosol explosion development in the experimental mine working. Thus, a thorough analysis made it possible to identify areas of explosion development in different zones of the experimental mine working. It was established that the arrangement zones and the explosion development areas might not coincide in their linear dimensions.

In particular, during the initiation of a coal dust explosion with the help of a methane and air mixture, the conditions for the explosion of a hybrid mixture of methane, dust and air are created at the borders of gassed (*I*) and dusty (*II*) zones. It is theoretically justified that in this case the released energy is much higher than the energy released when only the dust explodes. The plot of the explosion front velocity reflects this phenomenon as a slope with a peak at the point of maximum velocity. It has been experimentally confirmed that at the end of the acceleration section (*a*) the velocity *Vi* of explosion propagation is significantly greater than during the studied dust explosion.

In the dusty zone of the experimental mine working (*II*), the energy of the explosion is determined by the process of oxidation of coal particles and generally obeys expression (3) taking into account the mass of coal suspended in the air. The velocity of the fire front depends on the rate constant of the carbon oxidation reaction. This indicator depends on a number of factors, such as type of coal, its particle-size distribution, pressure, temperature, the presence of moisture and inorganic impurities, the concentration of fuel in the aerosol, etc. According to literature sources, the theoretical burning temperature of hard coal reaches 2010 to 2020°C. At the specified temperatures, the coal oxidation rate constant is $k_v=2 \cdot 10^{12}$ to $2 \cdot 10^{24}$. This explains the high velocity of the fire front and the derived shock front in the direction of the concentration of oxygen and fuel. The presence of moisture, impurities in dust that phlegmatize oxidation, the lack of oxygen can slow down the combustion process. It is known that despite the fact that such fronts are interconnected inseparably, the velocity of the shock front usually exceeds the velocity of the fire front (**Kostenko et al., 2022; Romanchenko et al., 2022; Cybulski, 1973**). It can be assumed that the fire front moves as the coal aerosol burns out. The movement of the shock front is facilitated by the relatively higher propagation velocity of the seismic waves generated by the explosion in the rock mass. Such a velocity difference explains the intermittent separation of the shock front, and the development of the wave nature of the dust explosion propagation with an average velocity of V_{min}-V_{max}. The wave propagation of the explosion also contributes to the uneven transition of dust deposits to the state of the curtain and the unstable content of fuel in the aerosol.

The obtained experimental data on the velocity of propagation of the explosion front in the experimental mine working are the basis for substantiating the speed of operation of automatic means of suppressing explosions, for example, to select the distance between the sensor and the actuator (**Kostenko et al., 2021**). The availability of technological equipment, fastening equipment and rail vehicles help to suppress the intensity of an explosion. On the contrary, the presence of belt conveyors will increase the intensity of an explosion.

At the last stage of the movement of the experimental explosion, when its front passes through the dust-free section (*III*), the inhibiting effect of the slow burning of the aerosol does not occur, and the shock front accelerates to V_g if there is a crater *b*. If section (*III*) is missing, the acceleration effect is absent.

The linear dependence between the cross-sectional plane and the amount of explosive energy developed there is justified theoretically. The given results can be used, in a first approximation, as a basis for justifying the speed of an operation as a means for suppressing the negative factors of coal dust explosions in mines. This allows for the application of this dependence to calculate the strength indicators of the protective structure based on the results of the obtained experimental data for the coal of a certain deposit.

To this end, it is possible to apply experimental data from the tests of the velocity of propagation of the explosion front in experimental set-ups of small cross-section, e.g. V_{max}, and also, knowing the cross-sectional area of the mine working *S*, to calculate the energy of the explosion, guided by expressions (5-6). This allows for a justification of the length of a dust barrier with inert load or a water barrier with shelves and vessels of standard size, calculating the strength parameters of a mechanical curtain, etc.

It makes sense to continue further research in the direction of broadening the understanding of the dynamics of the front movement of explosions of hybrid dust and gas mixtures. This will become the basis for improving the methods and means of both prevention and containment of underground accidents of this type with the help of systems of localization of coal dust explosions (**Kostenko et al., 2021**).

6. Conclusions

The velocity of propagation of the explosion front and the resulting energy are fundamental criteria in the creation of the means of containment of coal dust explosions in the network of coal mine workings. They determine the speed of an operation and the strength characteristics of the means of containment of coal dust explosions in mine workings.

It is proposed to supplement the mechanism of explosion development with an idea about the sections of development of explosion dynamics, i.e. initiation, dust explosion, crater, which determine the characteristic parameters of the explosive front velocity: maximum initiating velocity, average velocity, and maximum velocity in a crater.

It was established that during methane initiation in the experimental mine working at the boundary between the initiation and dusting zones, there is a situation of a hybrid explosion of a mixture of methane and dust with air, which has its own velocity and energy indicators.

One of the possible explanations for the wave-like nature of the movement of the coal dust explosion front through the mine working can be the difference in the velocity of the physical and chemical reaction of carbon oxidation and the propagation of shock waves in the rock mass.

A linear dependence of the energy generated during the coal aerosol explosion on the cross-sectional plane of the mine working was established. This makes it possible to use the results of testing the coal from certain deposits in small-scale experimental set-ups to justify the parameters of protective means for actual mine workings.

7. References

Cybulski, W. (1973): Wybuchy pyłu węglowego i ich zwalczanie, “Slask”, 451 pp.

Devi, P. M., Aamir, A., Sikandar, A. (2017): Rock dust requirement for suppression of coal dust explosion in underground coal mines in India-An investigation. International Conference on NexGen Technologies for Mining and Fuel Industries, 1, 425–432.

Eades, R., Perry, K. (2019): Evaluation of a 38 L explosive chamber for testing coal dust explosibility. Journal of Combustion, 2019, 5810173. https://doi.org/10.1155/2019/5810173.

Harris, M.L., Sapko, M.J. (2019): Floor dust erosion during early stages of coal dust explosion development. International Journal of Mining Science and Technology, 29(6), 825 – 830. https://doi.org/10.1016/j.ijmst.2019.09.001.

Kostenko, V., Zavialova, O., Pozdieiev, S., Kostenko, T., Hvozd, V. (2022): Mechanism of development of coal dust continuous explosion in a network of mine workings. Rudarsko-geološko-naftni zbornik, 37(1), 45-53. https://doi.org/10.17794/rgn.2022.1.5.

Kostenko, V., Zavialova, O., Novikova, Y., Bohomaz, O., Krupka, Y., & Kostenko T. (2022): Substantiating the parameters of quickly erected explosion-proof stopping. Rudarsko-geološko-Naftni Zbornik, 37(4), 143–153. https://doi.org/10.17794/rgn.2022.4.12

Kostenko, V., Zavialova, O., Pozdieiev, S., Kostenko, T., Vinyukov, A. (2021): Substantiation of design parameters of coal dust explosion containment system. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 3(447), 72–76. DOI: 10.17794/rgn.2021.2.10.

Man, C., Teacoach, K.A. (2009): Mining Publication: How Does Limestone Rock Dust Prevent Coal Dust Explosions in Coal Mines? Min.Eng, 61(9), 69-73.

Moradi, H., Sereshki, F., Ataei, M., Nazari, M. (2019): Experimental study of the effects of coal dust particle size on laminar burning velocity in a mixture of coal dust and methan. Rudarsko-geološko-naftni zbornik, 34(4), 47 – 55. DOI: 10.17794/rgn.2019.4.5.

Prostański, D. (2015): Experimental study of coal dust deposition in mine workings with the use of empirical models. Journal of Sustainable Mining, 14(2), 108–114. https://doi.org/10.1016/j.jsm. 2015.08.015.

Rodionov, V.A., Abiev, Z.A., Zhikharev, S.Ya. (2018): Methodology for investigation of stone dust combustion and detonation processes in mining, Bulletin of PNRPU. Geology. Oil & Gas Engineering & Mining, 17(1), 50-59. https://doi.org/10.15593/2224-9923/2018.1.5.

Romanchenko, S.B., Kosterenko, V.N. (2018): Coal dust explosions full- scale research and localization means efficiency criteria. Vestnik nauchnogo centra po bezopasnosti rabot v ugol'noj promyshlennosti, 4, 6-20.

Romanchenko, S.B., Sobolev, V.V. (2022): Promising solutions in the field of ensuring dustand explosion safety of mines. Vestnik nauchnogo centra po bezopasnosti rabot v ugol'noj promyshlennosti, 1, 6-13.

Wang, Y., Wang, H., Zhang, L., Hu, L. (2021): Experimental study on ignition of methane and coal dust on the surface of high temperature heat source. Industrial and mining automation, 47 (9), 85 – 9. https://doi.org/10.13272/j.issn. 1671-251x.17823.

Zavialova, O., Kostenko, V., Liashok, N., Grygorian, M., Kostenko, T., Pokaliuk, V. (2021): Theoretical basis for the formation of damaging factors during the coal aerosol explosion. Mining of mineral deposits, 15(4), 130-138. https://doi.org/10.33271/mining15.04.130.

SAŽETAK

Mehanizam razvoja eksplozije ugljenog aerosola u eksperimentalnim rudarskim radovima

Nema dovoljno znanstvenih podataka o razini energije i brzini eksplozije u stvarnim rudarskim iskopima, koji imaju veću površinu poprečnog presjeka od eksperimentalnih rudarskih radova. Cilj studije je potvrditi energetske parametre eksplozije u stvarnim rudarskim iskopima na temelju otkrivanja mehanizma razvoja požarne fronte pri eksploziji ugljene prašine u eksperimentalnom rudniku s ograničenim poprečnim presjekom. Ova istraživanja mogu biti temelj za odabir brzine djelovanja i jačine sredstava za lokalizaciju eksplozije ugljene prašine. Glavna metodologija istraživanja temelji se na eksperimentima i analitičkom postupku analize rezultata testnih eksplozija ugljene prašine u pokusnim rudarskim otkopima te teoretskom obrazloženju zakonitosti razvoja brzine i dodatne energije fronte požara buduće ekstrapolacije u uvjetima stvarnih rudarskih radova. Predlaže se dopuna mehanizma razvoja eksplozije u dijelovima, tj. inicijaciji, eksploziji prašine, plamenom krateru, koji određuju karakteristične parametre brzine eksplozivne fronte: maksimalnu početnu brzinu, prosječnu brzinu, maksimalnu brzinu u plamenom krateru. Utvrđeno je da tijekom inicijacije metana u pokusnom rudniku koja se odvija na granici između zone inicijacije i zone zaprašivanja dolazi do hibridne eksplozije mješavine metana i prašine sa zrakom, koja ima svoje pokazatelje brzine i energije. Utvrđena je linearna ovisnost energije nastale eksplozijom aerosola ugljena i površine presjeka rudničke prostorije. Time se omogućava korištenje rezultata ispitivanja ugljena iz pojedinih ležišta u manjim pokusnim otkopima za potvrđivanje parametara zaštitnih sredstava kod stvarnih rudarskih radova.

Ključne riječi:
rudarski radovi, ugljeni aerosol, eksplozija ugljene prašine, brzina eksplozivne fronte

Author's contribution

Viktor Kostenko (1) (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; **Olha Bohomaz** (2) (PhD) reviewed literary sources, processed and analyzed the results; **Tetiana Kostenko** (3) (doctor of technical sciences, professor) participated in all stages of work, submission and review of the paper and the completion of the literature review, analysis of the results; **Andriy Berezovskyi** (4) (PhD, associate professor) processed and analyzed the results.