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METHODOLOGY FOR INVESTIGATION OF STONE DUST COMBUSTION AND DETONATION PROCESSES IN MINING

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МЕТОДИКА ИССЛЕДОВАНИЯ ПРОЦЕССОВ ГОРЕНИЯ И ДЕТОНАЦИИ КАМЕННОУГОЛЬНОЙ ПЫЛИ В ГОРНЫХ ВЫРАБОТКАХ

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explosion, explosion pressure increase rate, coal dust, explosion pressure, combustion, aerosol, deflagration, detonation.

The paper presents results of the study of processes of coal dust detonation combustion obtained using a technique approved by the authors. The essence of the technique is the use of a specific coal dust fraction to study the explosion pressure, explosion pressure increase rate and transformation coefficient. It allows applying the results of a laboratory experiment to the actual data of explosion and combustion of dust and gas mixtures of mines that have a much larger volume. In other words it allows predicting the explosion pressure increase rate in relation to specific excavation of coal mines.
The methodology for studying combustion and detonation processes, briefly described in the article, is based both on requirements of modern regulatory documents and the practical experience of research institutes engaged in similar research. The practical component of the method is based on an installation which represents an explosive combustion chamber in the form of a sphere with a volume of 20 liters.
The data of detonation combustion are processed using application software and presented graphically in three figures. It is shown that dispersion composition of coal dust indluences on the explosion pressure, explosion pressure increase rate and transformation coefficient. Research work is carried out with a sample of coal of KS-type from a thick beam of the mine named after Dzerzhinskiy.
As a result of the analysis of digital and graphic data obtained during processing, it is proved that dust with fractional composition of 63-94 µm is the most explosive. It is revealed that explosion pressure increase rate changes as a function of dust concentration in the installation reaction volume in the way that there was two maxima of the explosion pressure increase rate where one was at 100 g/m^3 and the second at 400 g/m^3. The results obtained during determination of the explosion pressure increase rate have shown the necessity of a non-trivial, more thoroughtful approach to study explosion pressure increase and, consequently, determin the transformation coefficient. In addition, analysis of the experimental data presented in the article confirmed that during the development of means of flame retardation and explosion suppression used in automatic means for explosion localization it is necessary to carry out further investigations with the coal dust fraction equal to 63-94 µm. The results obtained in the work will allow starting the study of the processes of detonation combustion in a dusty air containing methane.

Ключевые слова:
взрыв, скорость нарастания давления взрыва, угольная пыль, давление взрыва, горение, аэрозоль, дефлаграция, детонация.

Приведены результаты исследования процессов детонационного горения каменноугольной пыли, полученные с помощью апробированной авторами методики, сущность которой заключается в использовании конкретной фракции каменноугольной пыли для исследования давления взрыва, скорости нарастания давления взрыва и трансформационного коэффициента. Он позволяет применить результаты лабораторного эксперимента к фактическим данным взрыва и горения пылегазовоздушных смесей горных выработок, имеющих значительно больший объем, т.е. дает возможность спрогнозировать скорость нарастания давления взрыва применительно к конкретным горным выработкам угольных шахт.
Методика исследования процессов горения и детонации, кратко описанная в статье, основана как на требованиях современных нормативно-правовых документов, так и на практическом опыте научно-исследовательских институтов, занимающихся аналогичными исследованиями. В основу практической составляющей методики положена установка, представляющая собой взрывную камеру сгорания в виде сферы объемом 20 л.
Данные процесса детонационного горения обработаны с помощью прикладного программного обеспечения и представлены в графическом виде на трех рисунках. Наглядно показано влияние дисперсионного состава каменноугольной пыли на давление взрыва, скорость нарастания давления при взрыве и трансформационный коэффициент. Научно-исследовательская работа проводилась с образцом каменного угля марки КС, пласт Мощный, шахта им. Дзержинского.
В результате анализа цифровых и графических данных, полученных в ходе обработки, доказано, что наиболее взрывоопасной каменноугольной пылью является пыль фракционного состава 63–94 мкм. Выявлен неоднозначный эффект изменения скорости нарастания давления взрыва в зависимости от концентрации пыли в реакционном объеме установки, а именно наблюдалось два максимума скорости нарастания давления взрыва, один при 100 г/м^3 и второй при 400 г/м^3. Полученные результаты определения скорости нарастания давления взрыва показали необходимость нетривиального, более тщательного подхода к ее исследованию и, как следствие, к определению трансформационного коэффициента. Кроме того, анализ экспериментальных данных, приведенных в настоящей статье, подтвердил, что при разработке эффективных средств огнепреграждения и взрывоподавления, применяемых в автоматических средствах локализации взрыва, необходимо проводить дальнейшие исследования с фракцией каменноугольной пыли, равной 63–94 мкм. Полученные в работе результаты позволят перейти к изучению процессов детонационного горения в пылевоздушной среде содержащей метан.

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Introduction

Control of methane and coal dust explosions is one of the most urgent problems of ensuring safe working conditions in coal mines. It is known that in the case of a poor state of dust explosion protective devices even local explosions of methane or suspended coal dust that happen in a place of mine workings can spread over a considerable distance [1–5].

In recent years, dust formation and volume of gas in mine working increased sharply due to intensification of coal mining and complicated mining, geological and technical conditions. That has led to a high danger of explosions [2, 6–10].

The scientific and technical information given in [10, 11], as well as the factors mentioned above, confirm the need to timely determine the detonation properties of coal dust, formed in the current conditions of coal mining. After, it is necessary to scientifically substantiate the screening for devices of explosion damaging factors suppression (flame front/ shock wave etc.), including high effectiveness fire extinguishing/explosion suppression devices [9, 11].

The purpose of the paper is to study the processes of combustion and detonation of coal dust in mine workings to determine the maximum explosion pressure, explosion pressure increase rate and transformation coefficient, which allows correlating the results of laboratory studies with mine space.

Object of the study

The object of the study are KS-type coal samples from the Moshchny seam of mine named after Dzerzhinskiy, which is classified as super dangerous in terms of dust and gas. The seam Moshchny refers to a very prone to spontaneous self-combustion. There is a minimum yield of volatile substances in coals of all strata in the mine field equal to 17.3 %. According to the "General safety rules", dust with the release of volatile substances of more than 10 % is explosive one [10, 12].

Samples of fractional composition of 63-94 μm were used when performing a study of combustion processes and detonation properties of coal dust. Screening for that fractional composition is not accidental and is explained by the data given in [10, 13–17], where it is shown coal dust of that fractional composition is the most explosive and is formed in a larger amount during the coal mining (with its grinding).

Methods and procedures of the study

The study is performed usign an approved method by the authors of the article decribed in [13, 18]. Results of the study are presented in this article. In addition, requirements and recommendations on how to apply methods for assessing the explosive and fire hazard properties of coal dust aerosols described in the works of other authors [14, 19–26] are taken into account.

Laboratory studies of the processes of detonation combustion of coal dust air aerosol were carried out on an installation made on the basis of an Austrian license by the Institute of Industrial Explosion Protection (China), built at the Saint-Petersburg Mining University.

The installation is shown in Fig. 1.

The procedure (general algorithm) for carrying out the laboratory study is as follows: an aerosol of coal dust is injected at a single moment by compressed air at pressure of 2 MPa to the closed combustion chamber of the installation shown in Fig. 1.

The main technological operations in the tests are given below:

– sample preparation (grinding of coal to the working fraction, i.e. grinding on a vibratory cone mill-crusher; VKMD-10 was used)

– granulometric sieving (obtaining the required fraction with the particle size of sand dust in the range of 63–94 μm);

– air-dry drying;

– sampling by quarting for weighing and obtaining the required sample mass;

– loadng of the sand dust sample into the boot device of the installation;

– testing according the installation manual and authors' data [24, 25].

Fig. 1. The installation: *1* – feeding device (dust collector with a volume of 0.6 dm^3); *2* – inspection window; *3* – working chamber with an internal volume of 20 liters; *4* – holders and locking mechanism of the 20-liter sphere (working chamber); *5* – manometer; 6 – current conductors (holders of a chemical combustion); *7* – water outlet

According to the methods described in [19–21], it is recommended to carry the ignition of the dust-air mixture with a delay of 60 ms.

Considering the recommendations given in [22, 23], a composition of 2.4 g was chosen as chemical igniter.

A zirconium powder, nitrate and barium oxide were used as the main components of chemical igniters. There were two igniters simultaneously used in the installation. The igniters allowed obtaining a total energy of 10 kJ.

The pressure created by two such ignitors was 0.19 ± 0.01 MPa. Results of ignition of the formed inside the working chamber of a coal dust aerosol of a given concentration (in particular the explosion pressure and rate of explosion pressure increase) were automatically fixed by the data processing system.

After the test, a graph with dynamics of pressure changes in the volume of a 20-liter sphere (an explosive chamber) was analyzed. As for example Fig. 2 shows the test schedule for the explosive characteristics of one of the coal dust samples with determined parameters.

Explosion pressure P_{ex} is a maximum surplus pressure that occurs during deflagration combustion of a gas, vapor or dust-air mixture in a closed vessel at an initial pressure of the mixture equal to 101.3 kPa. The pressure should be defined as the arithmetic mean using the three tests.

Combustion time t_1 is a time difference between ignition activation and culmination point.

Induction time t_2 is the time difference between ignition activation and intersection of a tangent curve with the 0 MPa line.

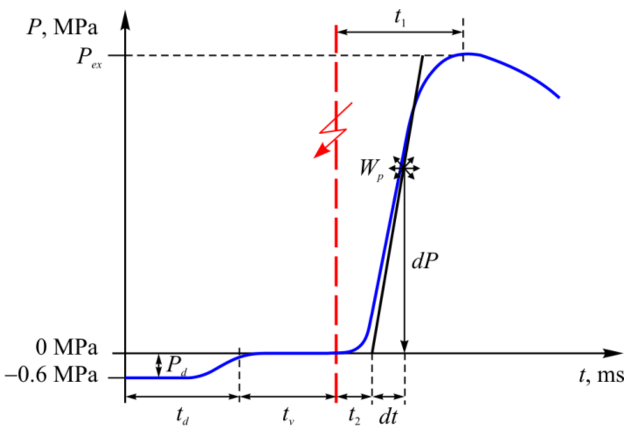

Fig. 2. Graph of pressure changes (P, MPa) during the time (t, ms) of combustion of a dust/gas mixture in the explosion chamber: P_d – rarefaction pressure of the combustion chamber; P_{ex} – explosion pressure; t_d – time delay of the exhaust valve; t_1 – combustion time; t_2 – induction time; t_v – ignition delay time; W_p – the inflection point in the increasing part of the pressure curve; dP/dt – explosion pressure increase rate

Rarefaction pressure in the combustion chamber P_d is the difference between the "preliminary vacuum" and normal pressure (standard value is 0.55–0.7 MPa).

Temporary retention of the exhaust valve t_d is the time between electrical activation of the valve and beginning of pressure increase in the installation (should be in the range of 30–50 ms).

Ignition delay time t_v influences the degree of turbulence (an important initial parameter).

W_p – the inflection point in the increasing part of the pressure curve.

Explosion pressure increase rate dP/dt is the ratio of the increment of the pressure created during the explosion in a closed vessel, to the time interval during which this increment occurred. The value of explosion pressure increase rate is used in the development of measures to ensure fire and explosion safety of technological processes. It is defined as the maximum of the tangent slope at the inflection point W_p in the growing part of pressure increase curve in time.

Results and discussion

The results obtained were processed using the applied software. Based on the data obtained there was a plot built representing the function of change in coal dust explosion pressure on concentration and detonation burning time of a dust/gas mixture (Fig. 3*a*). The graphs of change in explosion pressure and explosion pressure increase rate versus time were built as well (Fig. 3*b*) (pressure-time).

While determining the dependence of change in explosion pressure on concentration and rate of explosion from concentration of coal dust in the volume of the blasting chamber, we applied the recommended step for the mass amount of dust necessary to create a concentration in the volume of the 20-liter sphere. For example, we applied a step not exceeding 50 % of the original value for low concentrations, equal to 50 % for high concentrations and more than 50 % of the initial value for the last stage. In accordance with our methodology used, based on the data of [13, 18,

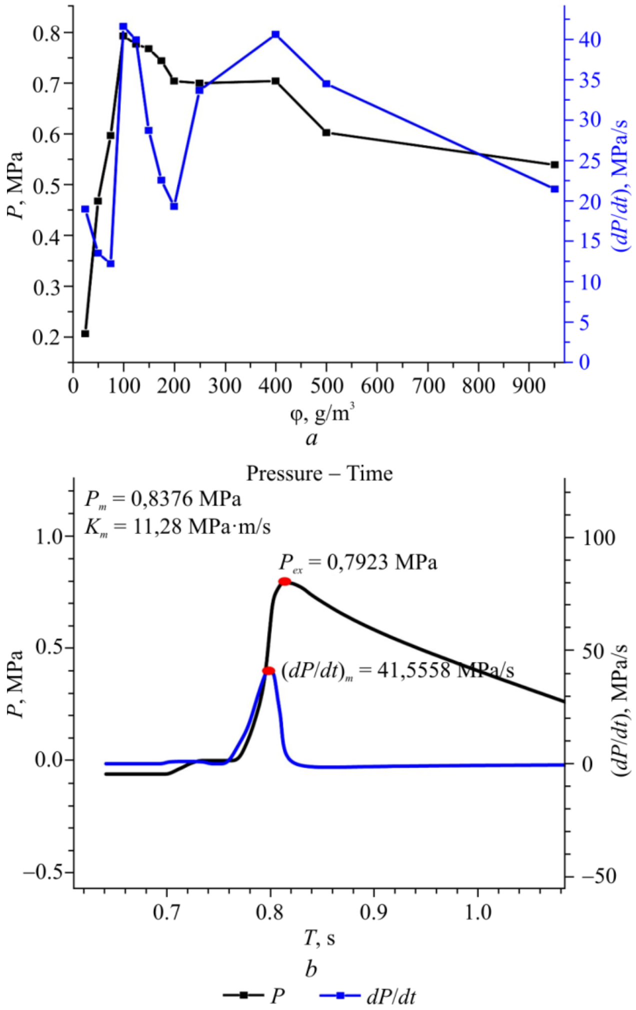

Fig. 3. Graph of explosion pressure change P and explosion pressure increase rate dP/dt: *a* – on coal dust concentration φ in 20-liter volume of the sphere (explosion chamber); *b* – on time T

19–21] and taking into account the information contained in [27–29], the results obtained are presented in the table.

According to the table, an ignition area (detonation combustion) is wide enough (from 50 to 950 g/m^3).

Results of laboratory experiments to determine the coal dust concentration influence on the explosion pressure and rate of explosion pressure increase rate are shown in Fig. 3*a*.

The analysis of Fig. 3 shows that explosion pressure increase rate hardly changes in a rather wide concentration range in particular 175–400 g/m^3 (175, 200, 250, 400): from P_{exp} = 0.74 MPa at

φ = 175 g/m^3 to P_{exp} = 0.7 MPa at φ = 400 g/m^3. Further increase in coal dust concentration in the reaction volume leads to a slow decrease in explosion pressure. There were two failures at concentration of 950 g/m^3 and no ignition of dust-air mixture at concentration of 1000 g/m^3.

Results of the detonation combustion (explosion) experiment in the volume of the 20-liter sphere during its burning by a chemical igniter with the energy of 10 kJ

No. of experiment	Dust concentration, g/m^3	Explosion
1	25	No
2	50	Yes
3	75	Yes
4	100	Yes
5	125	Yes
6	150	Yes
7	175	Yes
8	200	Yes
9	250	Yes
10	400	Yes
11	500	Once no, twice yes
12	600	Once no, twice yes
13	950	Twice no, once yes
14	1000	No

While carrying out the scientific and experimental work aimed to study the dependence of change in explosion pressure increase rate on coal dust concentration, we obtained results that could not explain immediately. For example, the maximum rate of increase in pressure (dP/dt) is observed at a concentration of 100 g/m^3 and then with a further increase in coal dust concentration it falls sharply. However, a second explosion pressure increase rate was observed starting from 200 g/m^3, that reached its maximum at φ = 400 g/m^3 and then slow fall slowly dP/dt.

As a result of the study of dust concentration influence on explosion pressure, the concentration of coal dust equal to 100 g/m^3 was selected for further studies (see Fig. 4) and work was continued to determine the most effective flame-extinguishing and explosive-suppressing powder compositions.

The result of processing in OriginPro software of automatically detected detonation combustion data of a dust-air aerosol of dispersion (fraction) 63–94 µm in a 20-liter explosion chamber (sphere) is given in Fig. 3*b*.

In accordance with the methodology, three experiments with the same sample of coal dust (by mass, dispersion etc.) were performed and final graph was built presented in Fig. 3*a*.

According to the experimental data obtained by us during the KS-type coal dust detonation combustion of the Dzerzhinskiy mine, the maximum explosion pressure was uqeal to 0.7923 MPa (7.9 atm or 792.3 kPa), i.e. P_{in} = 0.7923 ($^1P_{\min}$ = 0.7684, $^2P_{\exp}$ = 0.7719 and $^3P_{\max}$ = 0.8376 MPa).

Pressure increase rate was 41.558 MPa/s.

The transformation coefficient K_{m} calculated by the applied software of the laboratory installation was equal to 11.28 MPa·m/s.

According to the data presented in [17], if the transformation coefficient is known then it is possible to calculate the explosion pressure increase rate in any volumes, including mine workings.

The results obtained conform well with previously determined data given in [19, 24, 25, 29, 30].

Considering the fact that during the process of determination (investigation) of explosion pressure increase rate a number of difficulties was obtained (see the description of Fig. 3 above), the more attention will be paid for further scientific and research work.

Conclusions

1. Explosive and dangerous characteristics of KS-type coal dust of Moshchny seam Dzerzhinskiy are studied. The maximum recorded explosion pressure was 0.8376 MPa (P_{m}). It was confirmed that dust fractions with a dispersion of 63-94 µm at a concentration equal to 100 g/m^3 have a large maximum explosion pressure.

2. The second growth (increase) in explosion pressure rate could be observed in the region of high concentrations. The maximum explosion pressure increase rate was dP/dt = 41.558 MPa/s at φ = 100 g/m^3. The second rate increase is observed from φ = 200 g/m^3 to φ = 400 g/m^3. Herewith dP/dt = 40.5 MPa/s, which is lower the peak at φ = 100 g/m^3. We consider that it is reasonable to continue studying the behavior of explosion pressure increase rate depending on concentration of coal dust in the reaction volume of the installation.

3. It is determined that because of the large spread of dP/dt values (which is more than 15 %), there is a need to determine the arithmetic mean for the data of more than three measurements or to determine the reason for the variance of values and develop measures to eliminate it.

4. In our opinion it necessary to continue work in this direction and in order to identify an effective fire-extinguishing and explosive-suppression composition for φ = 100 g/m^3 to carry out the investigations both in the air environment and in medium containing methane.

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