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Determination of explosion parameters of hybrid mixtures

Manzhos Evgeny Vitalievich

ORCID ID: 0000-0003-0382-2774

Voevodsky Institute of Chemical Kinetics and Combustion SB RAS,

Novosibirsk, Institutskaya str. 3., junior researcher,Russia.

Corresponding Author:** ***Manzhos Evgeny Vitalievich, *Voevodsky Institute of Chemical Kinetics and Combustion SB RAS,*

Abstract: *A common phenomenon that plays a leading role in ensuring fire and explosion safety of work with dust and gas mixtures is described: a hybrid mixture. Historical information is provided and the current state of the problem is defined. The necessity of studying such mixtures, as an example, for coal basins, is emphasized. The methods used in the world for determining the explosion parameters of hybrid mixtures – the maximum explosion pressure, the lower concentration limit of flame propagation, the minimum explosive oxygen content and the minimum phlegmatizing concentration of the phlegmatizer - are briefly considered. An experimental installation recommended for use in the Russian Federation is also considered in detail. The manufactured design of such an installation with the necessary additions is described. The results of experimental studies are presented, showing the need for further research and the possibilities of using such experimental installations in various fields of industry are described.*

Keywords: *A hybrid mixture. Explosion indicators. Experimental setup. Research on hybrid mixtures. Application areas*

1. Introduction

As is known, some dispersed materials moving inside apparatuses and in the air environment of production areas can form flammable aerosols or so-called hybrid (combined) mixtures.

Such mixtures are dispersed systems consisting of small (less than 0.01 mm) solid or liquid particles (droplets), which are a dispersed phase, and a dispersion medium in the form of air or a mixture of gases [1].

According to the definition given in various regulatory documents describing, in addition to explosive atmospheres, ensuring the explosion protection of equipment and the rules for safe operation with it; a combined mixture is a mixture with air of combustible substances in different physical states. An example of a combined mixture may be a mixture of methane and coal dust with air. Research aimed at studying such mixtures began a long time ago [2] and is currently ongoing [3, 4, 5].

The main danger that arises when working with such a mixture is that a mixture of individual substances in concentrations that are non-explosive under normal conditions becomes explosive when combined [6]. For this reason, the operations associated with them require special attention to ensure maximum work efficiency and equipment safety.

The formation of such mixtures is possible as a result of any processes associated with the mechanical grinding of solids, steam condensation or solidification of sprayed liquid metal, crushing or crushing of chips. Similar processes occur in the chemical, pharmaceutical, mining, energy [7, 8, 9], and food industries [10].

In [11, 12], the mechanism of formation of a nanoscale aerosol during the mechanical destruction of coal from Kuzbass mines was investigated. A diffusion aerosol spectrometer was used to measure the concentration and size spectrum of aerosol particles in lava when a cleaning combine was running. It was found that 90% of the particles have a size of less than 200 nm. At the same time, there are two peaks in the nanoscale range corresponding to the average diameters of 20 and 150 nm: the first of them is caused by single particles, the second by aggregates consisting of single particles.

The effect of a carbon aerosol on the combustion of gas mixtures has been investigated. Laboratory experiments have shown that the presence of a nanoaerosol in a poor methane-air environment significantly increases its explosivity. This is manifested both in an increase in maximum pressure and in a significant increase in the rate of pressure build-up during an explosion. The conducted research allows us to conclude that the source of nanoaerosol are organic components contained in coal and released into the gas phase during local heating of coal on the teeth of the dredging combine.

In the coal-mining region of the Russian Federation, the Kuznetsk coal basin, research is underway [13, 14] aimed at ensuring the safety of work and the safety of equipment in coal mines both in the presence of combustible gas and coal dust in the production.

There are various organizations in the region whose activities are related to the prevention of fires and explosions at coal plants. For example, work is underway to prevent endogenous fires [15], but work is also planned to determine safe concentrations of coal dust and methane mixtures.

The relevance of conducting research on explosions of hybrid mixtures, in particular explosions in mixtures of methane, air and coal dust, is indisputable, since tragic events associated with the presence of such mixtures occur regularly, and the research itself is vital due to the large number of victims and destruction [16].

2. Regulatory documents

There are regulatory documents in the world that provide recommendations for handling explosive dust and gas mixtures. At the same time, it is noted that standards change very quickly and sometimes seem to contradict each other, but gradually regulations are becoming more conform.

In 2023, a literature review was published on the explosions of hybrid mixtures [17], which indicated the following: "To date, there is still no standardized equipment and procedures specifically designed to study the explosivity of hybrid mixtures."

But, nevertheless, in 2024, an article [18] was published, which, among other things, describes the methods used and the devices used to determine the explosion parameters of hybrid mixtures.

Gases at the Institute of Chemical Kinetics and Gorenje Gorenje of the Siberian Branch of the Russian Academy of Sciences (IHKG SB RAS).

Let's briefly review some of the installations and test methods used to determine the explosion hazard of hybrid mixtures. First of all, the tests are carried out in an explosion chamber with a volume of 1 m^3. Fig. 1 shows an explosive vessel of the specified capacity in the Laboratory of Physics and Chemistry of Combustion of Gases of the Institute of Chemical Kinetics and Combustion of the Siberian Branch of the Russian Academy of Sciences (ICKC SB RAS).

Fig1.*Explosive vessel in the ICKC SB RAS*

The tests can also be carried out in a CA20L explosion chamber with a capacity of 20 dm^3, also manufactured in the Czech Republic. The laboratory of Physics and Chemistry of Combustion of Gases has explosive vessels with a capacity of 10 liters and several vessels with a capacity of 3 liters, which can be used as explosion chambers.

An interesting standard is [19], which is in force in Germany, which provides data on the dangers of coal dust mixtures with air and hybrid mixtures. In addition to the explosive vessels described earlier, it provides a diagram of an explosive coal mine. There are active explosive coal mines in Poland and South Africa. There are no such mines in our country.

In the Russian Federation, the Ministry of Emergency Situations (EMERCOM of the Russian Federation) is responsible for ensuring fire and explosion safety. Instructions, rules and regulations for handling explosive atmospheres have been developed.

3. INSTALLATION

The current regulatory document in the Russian Federation is [20], which describes a method for experimentally determining the explosion parameters of dust—air mixtures - the maximum explosion pressure, the lower concentration limit of flame propagation, the minimum explosive oxygen content and the minimum phlegmatizing concentration of the phlegmatizer.

The ICKC SB RAS designed and manufactured installations for determining the explosion parameters of dust-air mixtures using the installation scheme given in the same regulatory document, but some parameters were refined during the manufacturing process [21]. The schematic diagram of the installation is shown in Fig. 2, the manufactured installation is shown in Fig. 3.

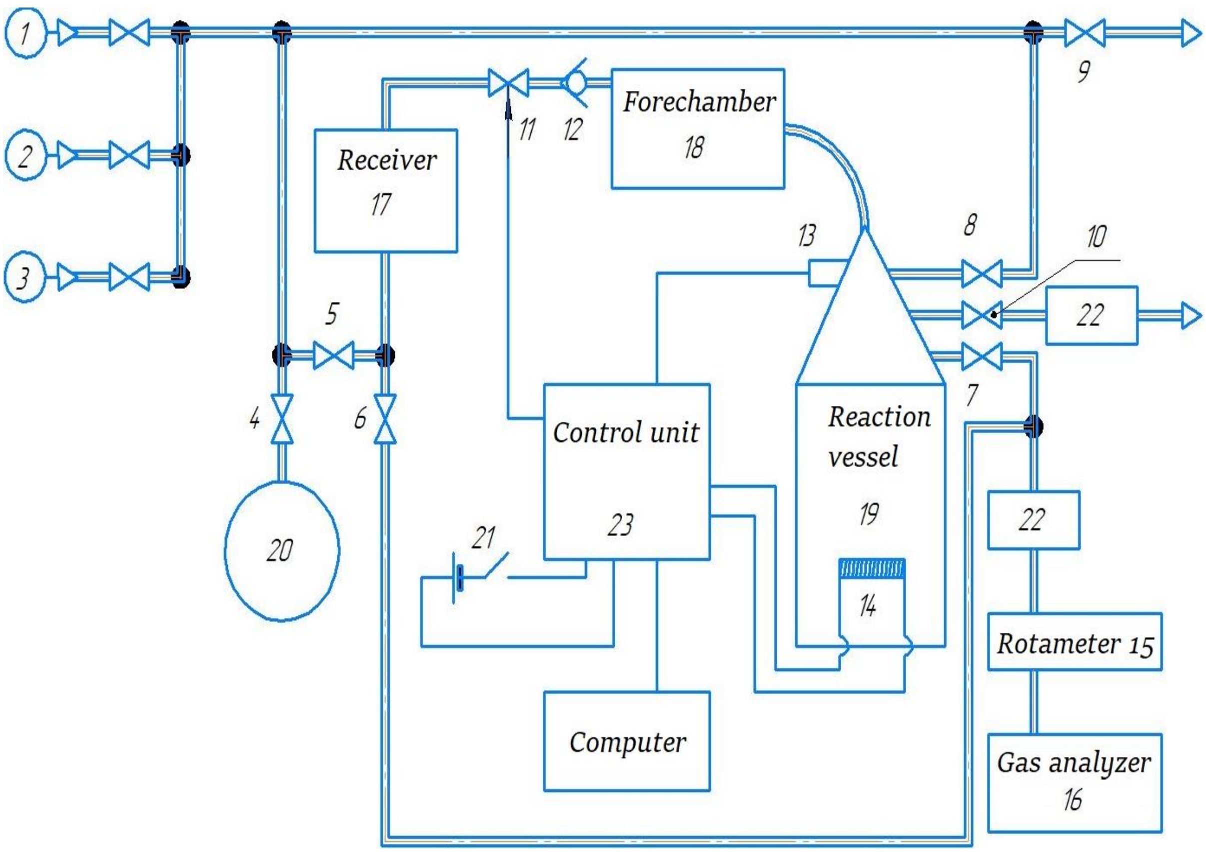

Fig2. *Schematic diagram of the installation for determining the explosion parameters of dust-air mixtures*

In the diagram: 1-3 valves for air, gas and phlegmatizer supply; 4 – pressure gauge valve; 5 – supply valve to the receiver; 6 – gas supply valve from the receiver to the gas analyzer; 7 – supply valve from the reaction vessel to the gas analyzer; 8 – valve for measuring pressure in the reaction vessel using a pressure gauge; 9 – valve pressure relief valve from the main line into the atmosphere; 10 – pressure relief valve from the reaction vessel; 11 – pneumatic distributor; 12 – non–return valve; 13 – pressure sensor; 14 – heating spiral; 15 – rotameter; 16 – gas analyzer; 17 – receiver; 18 – fore-chamber; 19 - reaction vessel; 20 – pressure gauge; 21 – power supply; 22- filter; 23 – electronic control unit.

Fig3. *Installation by definition parameters of explosion of dust-air mixtures*

The installation must ensure the determination of the parameters specified in the regulatory document for dust-air mixtures and is intended to work with dust-air mixtures with particle sizes: no more than 50 µm for metals and no more than 100 µm for other substances.

The Technology Readiness Level (TRL) corresponds to TRL7 — the technical feasibility has been proven, and a working prototype has been developed. The prototype has been demonstrated as part of a system under real operating conditions. The installation complies with the regulatory document [18]. The explosion parameters of lycopodium powder determined during experimental studies align with those specified in the regulatory document and are consistent with data from contemporary research [22].

4. RESEARCH AND RESULTS

Research on the installation was conducted in two main directions. The first direction involved studying its operational modes and verifying the compliance of explosion process parameters using a standardized dust sample—lycopodium powder according to GOST 22226-76. The second direction focused on obtaining experimental data with specific samples of coal dust.

Within the framework of the first direction, special attention was paid to the ignition process. It was found that some of the parameters of the ignition source proposed in the standard contradicted each other. The standard provides a schematic diagram of the installation, specifies the dimensions of its individual parts, and outlines the requirements for the materials used. Additionally, the loads acting on the components of the installation are indicated to ensure proper calculation and selection of their design parameters.

To study the combustion of coal dust in the presence of methane, a series of experiments were conducted on the combustion of two coal grades in a methane-air mixture with a methane content of 4.9 vol.%. The methane-air mixture was prepared in a mixer based on partial pressures with an accuracy of 0.1%, using technical methane of the following composition: CH_4 - 93.8%, C_2H_6 - 0.74%, C_3H_8 - 3.54%, C_4H_{10} - 0.9%; trace amounts of isopentane, pentane, cyclopentane, and isohexane were also present. According to document [23], the lower flammability limit of methane in air is 5.28%. In our case, a near-limit methane-air mixture with a technical methane content of 4.9 vol.% was used as the dispersion medium.

The results of the experiments are shown in Fig. 4.

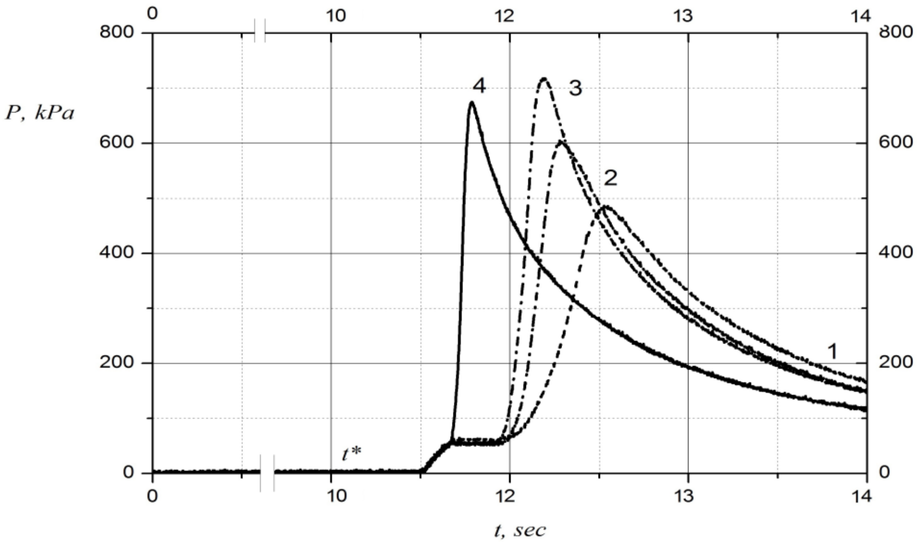

Fig4. *Dependence of pressure in the reaction vessel on the process timefor various concentrations and types of coal dustduring combustion in a methane-air mixture of 4.9 vol.%.*

0 - t ¬ Spiral heating time;*

t - Moment of the beginning of spraying*

1 – Methane-air mixture with a technical methane content of 4.9 vol.%;

2 – Methane-air mixture with the addition of 65 µm coal dust from "Baikaimskaya Energy" at a concentration of 72.5 g/m³;

3 – Methane-air mixture with the addition of 65 µm coal dust from "Baikaimskaya Energy" at a concentration of 131.1 g/m³;

4 – Methane-air mixture with the addition of 60 µm coal dust from "Belovsky" at a concentration of 149.8 g/m³.

The graph marked with the number 1 shows the change in pressure in the reaction vessel during the ignition of only the methane-air mixture without the participation of coal. It serves as a reference to compare the intensity of the impact of different coal dust grades on combustion. This mixture ignited after initial preheating.

It was found that the coal from "Baikaimskaya Energy" does not ignite in an air mixture. However, experiments with methane additives showed that this coal burns in the presence of a near-limit methane-air mixture. When added to a methane-air mixture with a technical methane content of 4.9 vol.%, this coal dust, in addition to the pressure increase from methane combustion, causes an additional pressure increase in the vessel of about 100-300 kPa (curves 2 and 3).

The maximum explosion pressure during venting without coal is approximately 500 kPa (curve 1). Adding a small amount of coal at a concentration of 72.5 g/m³ already increases the explosion pressure to 600 kPa. With a further increase in coal dust concentration, the explosion pressure reaches about 700 kPa (curves 4 and 5).

In our country, a similar installation was created at the All-Russian Research Institute of Fire Protection (VNIIPO) in Balashikha back in 1969. Currently, the installations manufactured at the Institute of Chemical Kinetics and Combustion (ICKC) are located in Yekaterinburg and Kemerovo. However, there is currently no unified theoretical framework or concept for testing dust-gas mixtures with particles of varying dispersity.

5. Conclusion

5.1 Refinement and Enhancement of the Experimental Setup

The experimental setup specified in the regulatory document for determining the explosion parameters of dust-gas mixtures has been refined and expanded. The design of the installation has been developed, and the units have been manufactured.

5.2 Experimental Studies

Experimental studies were conducted on the combustion of two coal grades from the Kuznetsk Coal Basin with the addition of near-limit methane-air mixtures. These studies demonstrated the role of mutual influence of combustible additives at concentrations close to the limit within the overall composition of the hybrid mixture.

5.3 Application of the Installation

The installation can be used for testing coal dust, as well as various substances generated in industries involving grinding, spraying, production of fine-grained materials, and aerosol formation. It is applicable in mining, chemical, pharmaceutical, and energy industries.

5.4 Need for Comprehensive Scientific and Technical Program (CSTP)

The participation and funding of a Comprehensive Scientific and Technical Program (CSTP) are necessary. This program should focus on developing recommendations and designing installations for determining the explosion parameters of hybrid mixtures and aerosols of various substances in the air of production zones or within technological pipelines.

This initiative will contribute to improving safety standards and operational efficiency in industries dealing with combustible dust and gas mixtures.

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