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The Choice of Optical Flame Detectors for Automatic Explosion Containment Systems Based on the Results of Explosion Radiation Analysis of Methane- and Dust-Air Mixtures

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Abstract: A review of the existing optoelectron monitoring devices revealed that the design of optoelectron detectors of the mine atmosphere does not sufficiently take into account the factor of external optical interference. This includes any extraneous source of thermal emission: a source of artificial lighting or enterprises. As a consequence, the optoelectron detectors -based safety systems currently installed at mining sites are not able to ensure properly the detection of the ignition source in the presence of optical interference. Thus, it is necessary to determine the working spectral wavelength ranges from methane and coal dust explosions. The article presents the results of experimental research devoted to the methane-air mixture and coal dust explosion spectral analysis by means of the photoelectric method. The ignition of a methane-air mixture of stoichiometric concentration (9.5%) and coal dust of size characterized by the dispersion of 63–94 microns and concentration of 200 g/m^3 was carried out in a 20 L spherical chamber with an initial temperature in the setup of 18–22 °C at atmospheric pressure. Then, photometry of the explosion light flux was conducted on a photoelectric unit. Operating spectral wavelength ranges from methane and coal dust explosions were determined. For the methane-air mixture, it is advisable to use the spectral regions at the maximum emission of 390 and 900 nm. The spectrum section at the maximum emission of 620 nm was sufficient for dust-air mixture. It enabled us to select the wavelength ranges for automatic explosion suppression systems' launching references. This will exclude false triggering of the explosion suppression system from other radiation sources. The research results will help to improve the decision-making credibility of the device in its direct design. The results will be used in further research to design noise-resistant optical flame detection sensors with a high response rate.

Keywords: explosion; coal dust; methane; explosion suppression; spectral characteristics; explosion pressure; radiation intensity; free radicals

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1. Introduction

Dust and gas explosions are among the greatest disasters in the coal industry and are related with mass fatalities. This is a danger for the entire mining industry, not just coal mining [1]. In this regard, safety improvement during blasting operations in gaseous and dusty mines is of utmost importance [2]. Dust-methane explosion safety upgrades are possible only by a comprehensive approach, including risk management [3–5], development of tools and methods of mine explosion protection, methane emission control [6], coal deposits underground mining technological processes monitoring [7–10].

Among the effective ways to control possible explosions are the automatic ignition prevention systems. The sensors applied in automatic explosion barriers respond to high pressure (outside rods) and temperature, abnormal concentrations of explosive gases, optical parameters and flames [11]. The disadvantage of the sensors, responding to the explosion wave pressure, is their possible actuation because of extraneous acoustic signals. The authors of [12] provide an explanation of the outside rods' inefficiency due to their

spatiotemporal parameters that are insufficient for successful explosion containment. The disadvantage of sensors, responding to the temperature changes, is their sensibility to the dusty mine environment, dust deposits, etc. [13]. Since the ignition process includes lighting, the perfect solution is optical sensors detecting dynamics in infrared and ultraviolet radiation and able to start the automatic prevention system to avoid combustion and explosions of methane-dust-air mixture.

The first thing we consider when estimating occupational injury risks is the air shock wave produced by methane-dust-air mixture's explosion [9]. Therefore, it's clear that an effective suppression system should be started at the very early ignition stages [14–16]. For this reason, the optical sensor's spectral response should be sufficient to start the suppression system.

There is one method [17,18] to measure object temperature without known emittance involvement. However, this method is not effective because of its slow response, due to the need to analyze and process a wide range of the optical spectrum [19]. In this regard, the correct choice of optical sensor is impossible without considering a specific flame and methane-dust-air explosion radiation spectrum.

A number of optoelectron devices (OEDs) have been proposed for use in fire detection and localization systems, including two spectral ratio optoelectron devices. The device uses radiation in three spectral ranges (750 $\pm$ 40 nm, 950 $\pm$ 50 nm, 1550 $\pm$ 12 nm). However, the study does not give a criterion for the choice of these ranges [20].

Moreover, for proper extinguishment within the development ratio with a cross-sectional area up to 10 m^2, it is necessary to create the explosion-suppressing environment by throwing out at least 30 kg of inhibitor within 15 ms. This throwing rate in case of false alarms can be dangerous for people located in the immediate vicinity to the explosion suppression devices [21].

Therefore, the development of construction and creation of a fast-operating OED control of explosive dust and gas atmosphere, insensitive to dustiness of the intermediate atmosphere and having a high probability of detecting the ignition source at an early stage in the presence of external optical interference, is an urgent scientific and technological task. It has an essential economic importance.

Thus, this research aims to obtain the spectral characteristics of combustion and methane-air mixtures' explosion radiation for the correct choice of input sensors applicable for explosion suppression systems.

2. Materials and Methods

The research into the flame radiation spectrum and methane, air and dust mixtures' explosion radiation spectrum was carried out by photoelectric method and aimed to obtain data on the nature of radiation energy wavelength distribution. This method enables spectrum recording with automatic dark signal subtraction and spectrograph wavelength calibration [22,23].

Currently it has been established [24,25] that gas radiation, heated by a shock wave, corresponds to "gray body" radiation, provided that the relative spectral energy distribution can be almost identified with any "black body" energy distribution at the temperature T.

The spectral-energy distribution of radiation emitted by a "black body" is described by the Planck formula:

$$B_\lambda = \frac{C_1 \cdot \lambda^{-5}}{e^{C_2/\lambda \cdot T} - 1}, \quad (1)$$

where B_λ is emitting surface spectral brightness, λ is emission wavelength, C_1 and C_2 are constants, and T is emitting surface temperature.

Provided that $C_2/\lambda \cdot T >> 1$, Formula (1) is reduced to the classic Wien formula, which gives quite an accurate description of shock wave spectral energy distribution for the visible area:

$$B_\lambda = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}}. \quad (2)$$

Formula (2) shows that for the curve reflecting spectral energy distribution of the luminous gases, which are gray emitters, it is necessary to provide its color temperature measurements.

The method of color temperature measurement is based on light intensity comparison from two spectrum areas.

Using Equation (2) we can have the following formula for energy ΔE, emitting by the body at the temperature T, wavelength λ and in the bandwidth $\Delta\lambda$:

$$\Delta E_{\lambda,T} = c_1 \lambda^{-5} \left(e^{-\frac{c_2}{\lambda T}} \right) \Delta\lambda. \quad (3)$$

If we know $\Delta E_{\lambda,T}$ for different wavelengths λ_1 and λ_2, it is easy to calculate the emitter temperature, when the reference source and temperature T_x are available.

We have:

$$\Delta E_{1x} = \Delta E \lambda_{1,T_x} = C_2 {\lambda_1}^{-5} e^{-\frac{C_2}{\lambda_1 T_x}} \Delta\lambda_1, \quad (4)$$

$$\Delta E_{2x} = \Delta E \lambda_{2,T_x} = C_2 {\lambda_2}^{-5} e^{-\frac{C_2}{\lambda_2 T_x}} \Delta\lambda_2. \quad (5)$$

Dividing Equation (3) by Equation (4) and taking logarithms, we have the following expression for the emitter under study:

$$\ln\left(\frac{\Delta E_{1x}}{\Delta E_{2x}}\right) = -5 \ln\left(\frac{\lambda_1}{\lambda_2}\right) + \ln\left(\frac{\Delta\lambda_1}{\Delta\lambda_2}\right) - \frac{C_2}{T_x}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \quad (6)$$

and for the reference source:

$$\ln\left(\frac{\Delta E_{10}}{\Delta E_{20}}\right) = -5 \ln\left(\frac{\lambda_1}{\lambda_2}\right) + \ln\left(\frac{\Delta\lambda_1}{\Delta\lambda_2}\right) - \frac{C_2}{T_0}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right). \quad (7)$$

From Equations (6) and (7) we have the equation for the source color temperature T_x calculation using the available temperature value of the reference emitter T_0:

$$\ln\left(\frac{\Delta E_{10}/\Delta E_{20}}{\Delta E_{1x}/\Delta E_{2x}}\right) = C_2\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \cdot \left(\frac{1}{T_x} - \frac{1}{T_0}\right). \quad (8)$$

A general algorithm of the laboratory experiment is the following: in a closed combustion chamber of a 20-L spherical explosion chamber [26–29] shown in Figure 1, we have a mixture of stoichiometric concentration, supplied by a single step by compression with 2 MPa pressure [30,31]. The accidents in coal mines mainly occur because of methane and coal dust explosions [1,32]. It is these two components that were the object of the study. Further, it is flamed with 60 ms delay. The initial temperature in the unit is about 18–22 °C at the atmospheric pressure. The tested samples were prepared using the partial pressure method. Then, before ignition, the mixture was stirred by circulation pump, to ensure its homogeneity [33]. A luminous flow produced by the combustible mixture ignition was observed through the explosion chamber watch window.

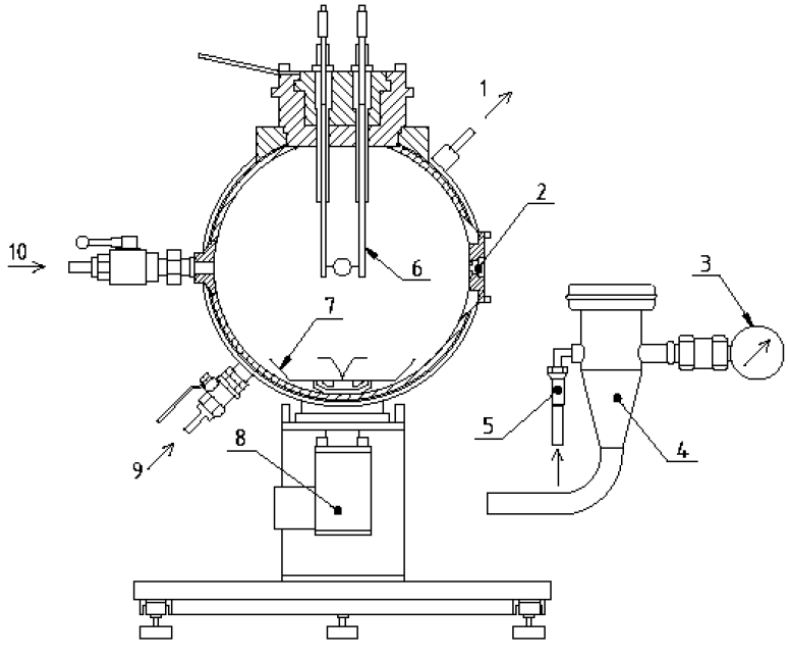


Figure 1. Twenty-liter spherical explosion chamber. The unit layout. 1—Water output, 2—pressure sensor, 3—pressure gauge, 4—dust collector 0.6 dm^3, 5—air intake, ignition source, 6—chemical igniters, 7—rebound sprayer, 8—fast-acting valve, 9—water intake, 10—air and resultant outlet.

The results of aerosol ignition of certain concentration, that was produced inside the chamber, as well as the explosion pressure and the explosion pressure rise rate are automatically recorded by the data processing system. This further data analysis enables us to conclude which is the successful ignition mixture (Figure 2).

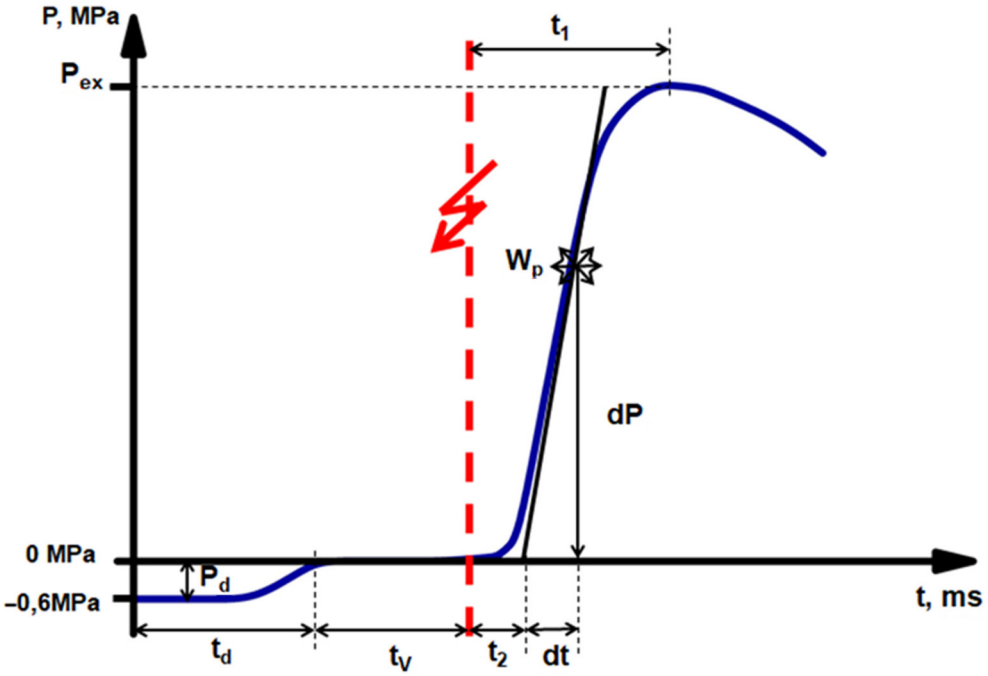


Figure 2. Pressure trend (P, MPa) for the period (t, ms) of dust-gas mixture combustion inside the explosion chamber: P_d—expansion pressure of the combustion chamber; P_{ex}—explosion pressure; td—exhaust valve delay; t_1—combustion time; t_2—induction time; t_v—ignition delay time; W_p—breakpoint in the rising part of the pressure curve; dP/dt—pressure rise rate at the explosion.

A pressure gauge with a response time of 0.2 ms is applicable for pressure measurements up to 2 MPa. Timing of pressure and flame radiation spectrum data recording from the ignition moment was controlled by ExTest software. To exclude the influence of the decomposition products of chemical igniters on the test result, the mixture was ignited by flash over. The energy produced from electrical initiation was 1 kJ.

Photometric measurement of light fluxes involved in the Equation (8) was carried out by means of photoelectric unit (Figure 3).

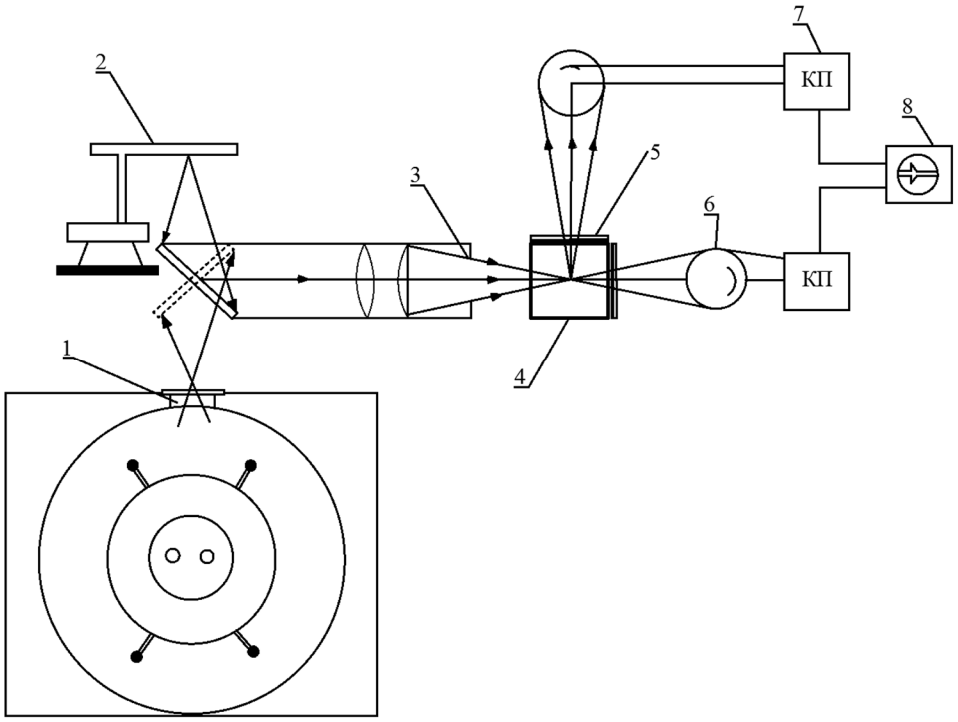


Figure 3. Basic diagram of temperature measurement. 1—Explosion chamber watch window, 2—band-lamp, 3—diaphragm, 4—splitter, 5—light filter, 6—photo multiplier, 7—cathode amplifier, 8—oscillograph.

The luminous flux was projected onto the inlet diaphragm of the unit using a rotatable flat mirror and lens. The luminous flux, after passing through the diaphragm, was recorded by photomultipliers using a beam splitting system, the signals of which were recorded from the oscilloscope screen. Two spectral intervals were separated by means of 15 nm bandpass interference filters.

The recording device was calibrated using standard stripe incandescent lamp. Its luminous flux was projected onto the inlet diaphragm of the unit through a hole in a rotating disk (chopper) using a rotary flat mirror and lens.

To measure the absolute radiation intensity, we used photomultipliers powered by high-voltage rectifier with electronic regulation.

For the radiator processes recording, it is necessary to consider not just the receiver's absolute sensitivity, but also the wavelength interval where this sensitivity remains effective.

One of the basic parameters of photodetectors is their time constant of the order of 10^{-8}–10^{-10} s.

The photomultipliers are characterized by significant photocurrent amplification factor and are well protected from the interferences caused by external electric fields. A relatively high input current of multistage photomultiplier enables to record output signals by cathode oscilloscopes without special broadband amplifiers involvement.

The oscilloscope's beam deviations are proportional to the radiation energy of the selected spectral intervals

$$D = \kappa \Delta E_1 \tag{9}$$

where D is oscilloscope beam deviation, and ΔE is defined by Formula (3). Using Equation (8) we have:

$$\ln\left(\frac{D_{10}/D_{20}}{D_{1x}/D_{2x}}\right) = C_2\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \cdot \left(\frac{1}{T_x} - \frac{1}{T_0}\right) \tag{10}$$

Let us denote the glow signals ratio of the investigated medium for the selected spectrum ranges by α, and the ratio of the calibration signals from a reference source at special color temperature T by β:

$$\alpha = D_{1x}/D_{2x} \tag{11}$$

$$\beta = D_{10}/D_{20} \tag{12}$$

If we substitute Equation (11) and Equation (12) into Equation (10) we'll get a working formula for source temperature calculation:

$$\ln(\beta/\alpha) = c_2\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \cdot \left(\frac{1}{T_x} - \frac{1}{T_o}\right) \tag{13}$$

If the reference source temperature is well known, then the temperature measurement error is calculated by the following formula:

$$\frac{\Delta T_x}{T_x} = \frac{\lambda_1 \cdot \lambda_2}{c_2(\lambda_2 - \lambda_1)} \cdot \left(\frac{\Delta\alpha}{\alpha} + \frac{\Delta\beta}{\beta}\right) \tag{14}$$

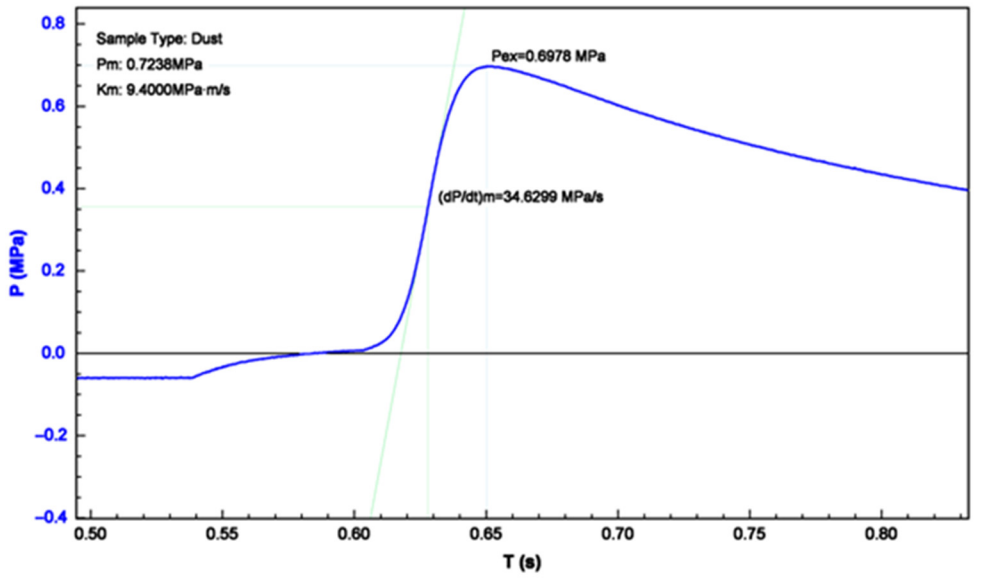
The measurement error is mostly because of the finite thickness of the oscilloscope beam and photoelectronic multiplier noises. According to the calculations, the relative error does not exceed 10%.

3. Results

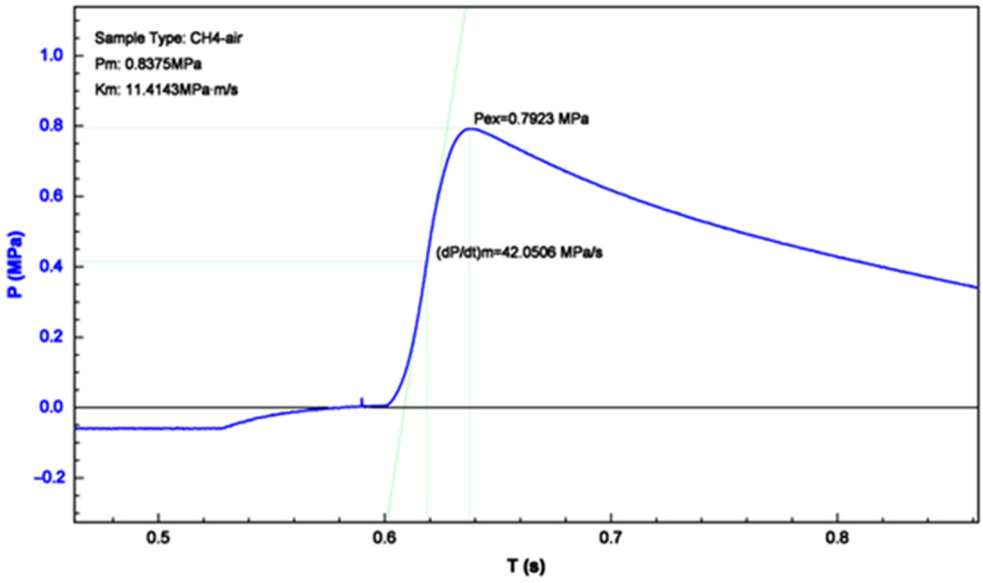
As shown in Figure 4a,b the mixture explosiveness assessment was carried out considering pressure values P_{max} and the explosion pressure rise rate $(dP/dt)_{max}$ [34]. To show the spectral radiation characteristics, the intensity (I) was recorded and analyzed as it is shown in Figure 5. Parameter I_0 is defined as the value at which the radiation intensity deviates from the baseline (I_0 is 110% of the initial radiation intensity) [35]. The parameter t0 shows the time necessary to reach the maximum value of radiation intensity.

According to the received experimental data, the ignited methane of stoichiometric concentration in chamber produced maximal explosion pressure P_{max} = 0.83 MPa and the rate of pressure rise was 42.05 MPa/s. When the explosive combustion of KS (KC) grade coal dust was registered in the Dzerzhinsky mine site, the maximum explosion pressure in the chamber was 0.79 MPa and the pressure rise rate was 34.62 MPa/s.

The results were analyzed using the application software. According to the obtained data, the graphs of changes in the pressure of methane and coal dust explosion were plotted against the time of explosive combustion of the mixture.



(**a**)



(**b**)

Figure 4. (**a**)Pressure-time curve based on CH_4 ignition (9.5% Vol.). (**b**) Pressure-time curve based on the results of the coal dust ignition (concentration 200 g/m^3, dispersibility 63–94 microns).

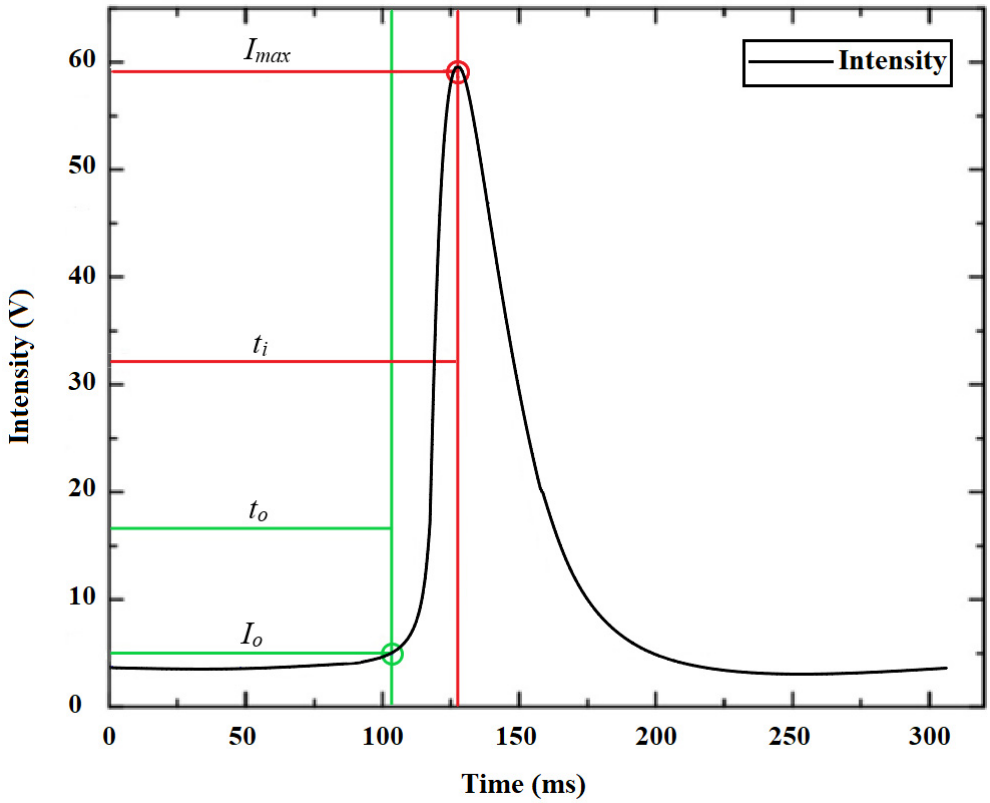


Figure 5. Maximum intensity of spectral radiation against time.

The results of experimental studies of radiation intensity measurement of methane-air and dust-air mixture explosion carried out by the electron-optical method are presented in the form of a dependence diagram, Figure 6.

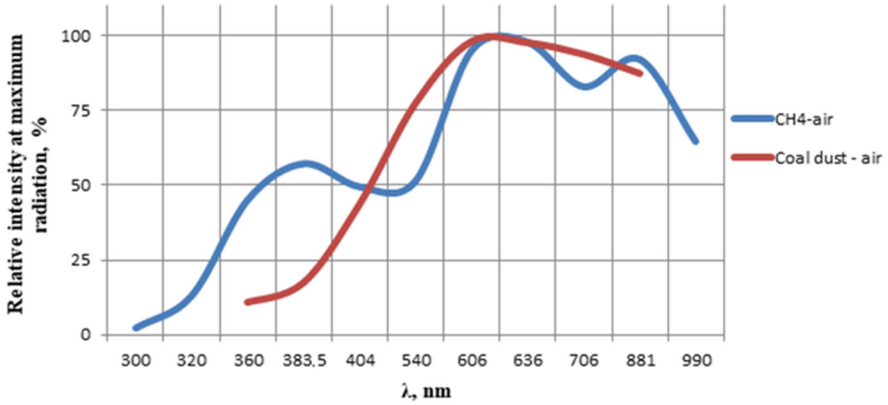


Figure 6. Spectral energy distribution at maximum radiation of methane-dust-air mixtures.

The relative intensity dependence on the wavelength shows that wavelength distribution of radiation energy differs from the Planck's type of distribution. The graph (Figure 6) clearly shows two peaks at the wavelengths λ_1 = 383.5 nm and λ_2 = 620 nm. These peaks appeared when the banded spectrum of molecules and radicals overlaid the continuous radiation spectrum of the heated gas.

The peak point in the range of λ = 390 nm can be identified with band system of the radical CH radiation [36], and the one in the range of λ = 620 nm–with the band system of the molecule C_2 radiation (Swan system). The band system of molecule C_2 is also in the range of λ_1 = 380 nm.

An intense series of bands are observed in the methane combustion spectrum, caused by the OH radical emission in the ultraviolet range of the spectrum λ_1 = 306 nm. The maximum radiation in the range of 900 nm should be identified with methane-air continuous combustion spectrum. In this case, the temperature, that was determined by the curve peak in accordance with Wien's displacement law, is T = 2610 K, which correlates well with the data received by spectrometric methods [37].

4. Conclusions

The availability of free radicals, which are considered the active centers of the chain reaction of methane explosion, is necessary for the entire process of explosive transition. Some free radicals, such as OH, H, O, CH_3, HO_2, CHO, are especially important not only for the explosion process, but also for the explosion suppression (inhibition) [38–40].

The flame spectrum analysis reveals the intermediate compounds formed during combustion and explosion and lets us study their behavior. Nowadays optical spectroscopy is the best method for free radical detection, since this method has no impact on the combustion and explosion process. The comparison of spectrum relative intensity enables us to get data on chemical reactions and involved radicals.

The resulting dependences of energy spectral distribution of explosions of methane-dust-air mixtures enable us to determine the central wavelengths of bandpass filters and select the spectral ranges for input sensors and explosion suppression.

Thus, for methane-air mixtures, it is reasonable to use spectral regions at the radiation maximums of 390 nm and 900 nm. This helps to avoid false triggering of the explosion suppression system possibly initiated by other radiation sources. For a dust-air mixture, it is enough to use one spectral region at the radiation maximum of 620 nm.

Thus, it is proved that for the development of an active explosion suppression system in coal mines, particular attention should be paid to the choice of working spectral wavelength ranges for the recognition of the desired signal.

The most important parameter for optoelectron devices is the credibility of the decision. It is a complex parameter and is determined by a combination of the following:

- Probability of fire detection in the absence of optical interference;
- False alarm probability;
- Probability of fire detection in the presence of external optical interference. The research results will help to improve the decision-making credibility of the device in its direct design.

We believe that further research should be devoted to initial combustion detection technology development with its further integration into multifunctional safety systems purposed for successful methane-dust-air combustion and explosion containment in coal mines and for the mines' industrial testing safety.

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