EXPERIMENTAL INVESTIGATIONS OF THE SPREAD OF PRODUCTS FROM INDUSTRIAL EXPLOSIVE COMBUSTION

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Cloud formation in the process of industrial explosive combustion has been experimentally investigated. The cloud of combustion products has been studied by thermal imaging, pyrometric, and spectrometric methods. Temperature fields of a combustion site are determined. Characteristic particle size is estimated. The obtained information can be used as initial data to solve problems of forecasting the evolution of the cloud formed by the combustion products and pollution of a locality.

Utilization of a waste from explosive production is accompanied by a number of phenomena that call for environmental ecological monitoring of a combustion site and adjacent regions. Gaseous emissions of CO, CO_2, NO, NO_2, etc. as well as emissions of small (of the order of 1 μm) carbon particles, metal oxides, and soil entrained by an ascending flow of combustion products have a major deleterious effect on the environment.

The cloud so formed, which contains the above-enumerated particles and gases, is dangerous for adjacent territories in case of its low elevation and for remote territories where the chemical compounds so produced may precipitate.

An analysis of factors affecting the ecological situation near the combustion site allows one to conclude that such parameters as the composition and the concentration of reaction products, the particle size and concentration, conditions of formation and displacement of the cloud of gaseous and condensed products, the cloud and surrounding temperatures, and the wind speed and the direction should be monitored.

A large volume of experimental information obtained by processing of the data of various measurement systems can be analyzed from the viewpoint of its applicability to an analysis of the ecological situation in the immediate vicinity from the explosive combustion site. Of interest are the results of measurements of the temperature of combustion products that affects the cloud evolution and elevation, of the particle size and concentration in the ascending air flow, and of the IR-emission spectrum of combustion products because this spectrum determines (qualitatively) their composition.

1. INVESTIGATION OF THE IR-EMISSION SPECTRA OF COMBUSTION PRODUCTS

It is well known that positions of the absorption and emission bands of gases are strictly specified. The presence of the absorption band in a certain wavelength interval unambiguously indicates the presence of a gas. The largest number of gaseous emission bands lies in the IR-wavelength range. To examine the qualitative composition of the cloud formed by combustion products, we analyzed the emission spectra of the products from combustion of explosive samples in the wavelength range from 1.5 to 5 μm. The spectra were recorded at distances of 6 and 135 cm from the sample with the BRS–1 transient spectrum analyzer.

Figure 1 shows the typical examples of the recorded spectra. Here, curve *1* is for a distance of 6 cm and curve *2* is for a distance of 135 cm from the sample. Vertical bars at the top of the figure show positions of the emission bands of chemical compounds most often encountered in the combustion products, namely, CO, CO_2, NO, etc.[1]

An analysis of the obtained emission spectra showed that 1) spectra are the functions of the distance from the sample and explosive composition, 2) bands of gaseous emission are seen in all spectra against the background of the black-body emission spectra, 3) intensities of the emission bands are high enough for their identification.

In particular, comparing the spectra shown in Fig. 1 and positions of emission bands of various gaseous compounds, we can identify emission bands of H_2O and CO_2 in the 2.5...3.0 and 4.0...4.5 wavelength ranges. Emission bands of these compounds are seen in all spectra irrespective of the sample composition and the distance from the sample to the observation point. For one sample at a distance of 6 cm from it we distinguished a band that can be identified with the 3.5-μm emission band of HCl. This can be explained by random impurities. In the spectra of samples of different composition recorded at a distance of 135 cm from the sample (see curve *2* in Fig. 1) we could identify the weak emission band of NO in the 2.6...2.7-μm wavelength range. The common features of the spectra recorded at a distance of 6 cm (see curve *1* in Fig. 1) are the

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intense emission bands of CO_2 and H_2O in the 2.0...2.7-μm wavelength range. Salient features of the spectra recorded at a distance of 135 cm from the samples are the emission bands of CO_2 and CO in the 4.2 ... 4.5 μm wavelength range.

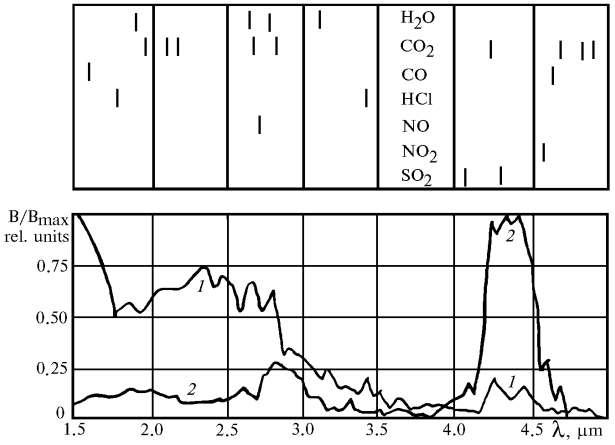

FIG. 1. Emission spectra of the combustion products.

Thus, the IR-emission spectra of the combustion products bear the information about their real composition. This allows one to monitor a change in the composition of the combustion products in the process of cloud evolution and precipitation and to forecast the formation of toxic chemical compounds responsible for the environmental pollution.

2. EXPERIMENTAL MEASUREMENTS OF THE DISPERSION COMPOSITION OF PRODUCTS FROM EXPLOSIVE COMBUSTION

The measurements of the average particle size were performed by the modified spectral transparency method (MSTM). In this method, the average extinction efficiency factor $\bar{Q}$ of sounding radiation is precalculated. It is assumed that this average extinction efficiency factor is invariant under the form of the particle size distribution function $f(a)$ in the context of the model for the interaction of radiation with condensed particles described by the Mie mechanism. The problem of determining the parameters of particles is reduced first, to measurement of the optical thickness of dispersed medium at several, for example, at two wavelengths λ_1 and λ_2, and second, to calculation of the average extinction efficiency factors $\bar{Q}$.

In the MSTM, additional information about optical parameters and particle size distribution function is used to determine the average particle radius. To estimate the effect of the uncertainty in the value of the complex refractive index of particles $m = n + i\varkappa$, where n is the refractive index and $\varkappa$ is the absorption coefficient of particles, which is caused by different nature of aerosol particles, we calculated the factors $\bar{Q}$ as functions of m for $n = 1.6 \ldots 2.0$ and $\varkappa = 3.5 \cdot 10^{-3} \ldots 3.0 \cdot 10^{-2}$. We established that uncertainty of m introduced the error in determining the particle size that does not exceed 4% for particles smaller than 1 μm and decreases as particle radius increases.

To estimate the effect of uncertainty of $f(a)$ on the result of determining the average particle radius, we calculated the dependence of $\bar{Q}$ on $f(a)$. We used the generalized gamma-distribution

$$f(a) = A\, a^{\alpha}\, e^{-ba^{\beta}},$$

that describes well the unimodal particle size distribution often encountered in physics of dispersed media as a distribution function. The parameters of the distribution varied in the following limits: $\alpha = 0.3 \ldots 2.0$, $\beta = 0.5 \ldots 2.0$, and the modal radius $a_0 = 0.1 \ldots 5.0$. The error in determining the average particle radius caused by uncertainty of $f(a)$ did not exceed 9%.

The measurements of the mean particle radius by the modified spectral transparency method were performed using a laser setup. Its block diagram is shown in Fig. 2. The optical thickness of the examined media τ varied from 6.7 to 13.8.

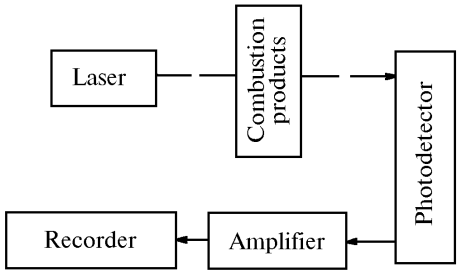

FIG. 2. Block diagram of the setup for measuring the average particle radius.

The average particle radius measured for four explosive samples was between 2.8 and 3.7 μm. Obviously, this is due to the soil particles entering into the ascending flow on which toxic chemical compounds may condense when they precipitate.

3. MEASUREMENTS OF THE TEMPERATURE OF COMBUSTION PRODUCTS

The temperature of the products from industrial explosive combustion was measured by the contactless method of pyrometry of the spectral ratio[3] (color pyrometry). The Spektropir–10 optical pyrometers of the spectral ratio were used mounted on a scanning platform at distances 8 ... 12 m from the explosive combustion site. The pyrometers were capable of measuring the temperatures in the range from 500 to 2800°C with errors no more than 1.5% for 0.05 s. Their sighting step varied from 1/25 to 1/500. The scanning platform provided means for rotation of the pyrometer by 90° about horizontal and vertical axes.

The temperature measured by scanning of the ascending flow of combustion products varied from 2100°C near the combustion zone to 800°C in the most distant regions of the flow. The temperature fluctuations were random in character and increased as the observation point moved away from a combustible substance. The temperature of combustion products is the most important parameter that determines rates of chemical processes and cloud evolution and displacement. Therefore, the results of measurements can be used as initial data for forecasting the cloud evolution and estimating the degree of pollution along the trajectory of cloud displacement.

4. DETERMINATION OF TEMPERATURE FIELDS IN THE EXPLOSIVE COMBUSTION SITE

The temperature fields in the explosive combustion site (fireyard) was measured by two methods. In the process of combustion, the temperature was measured with the help of the thermindex paint and melting temperature indicators. The temperature 15 ... 20 min after the combustion was measured with thermoelectric thermometers.

The termindex paint coated on a solid support changes its color at a transition temperature strictly specified for each paint. This provides a basis for the method of determining the temperature with the help of the thermindex paint. The melting temperature indicators change their colors when their heat–sensitive substances are melted and absorbed by color pigments.

We used seven temperature indicators that covered the temperature range from 84 to 475°C. These indicators were graduated under laboratory conditions with an error of 2°C.

We obtained the temperature fields of the explosive combustion site in the range 100 ... 400°C from combustion of three samples of explosives each having a mass of the order of several tons at distances up to 60 m from the combustion site correcting the location of the temperature indicators.

The temperature 15 ... 20 min after the explosive combustion was measured with the thermoelectric thermometers (thermocouples) XK graduated in the temperature range 0 ... 800°C and was recorded by the KSP–4 potentiometer having the temperature range 0 ... 200°C. The error of the recorder was no more than 1%. The measured temperature varied from 20 ... 50°C.

The data on the soil temperature allowed us to estimate the degree of thermal pollution of the environment and the thermal loads in the explosive combustion sites.

5. MEASUREMENTS OF THE TEMPERATURE OF THE CLOUD FORMED BY COMBUSTION PRODUCTS

The AGA-780 thermal imaging system was used to measure the temperature of a dust–gas cloud in the process of explosive combustion and after it. Images were recorded from two sites that provided the fields of view 800×800 and 200×200 m^2. The maximum temperatures in the cloud are given below as functions of the time from the start of combustion process.

Time, s	30	60	120	180	240
T, °C	220	120	110	110	background

Because combustion was observed in the daytime, the obtained data incorporated the error due to the scattered solar radiation that did not exceed 50°C in accordance with our estimates.

Typical thermograms made from the screen of the thermal imaging system 30 and 60 s after the start of combustion process are shown in Figs. 3 and 4, respectively. In Fig. 3, the cloud started to form and its temperature varied from 160 (zone *1*) to 220°C (zone *2*). In Fig. 3, the cloud occupied the entire field of view of the thermal imaging system (in this case, 200×200 m).

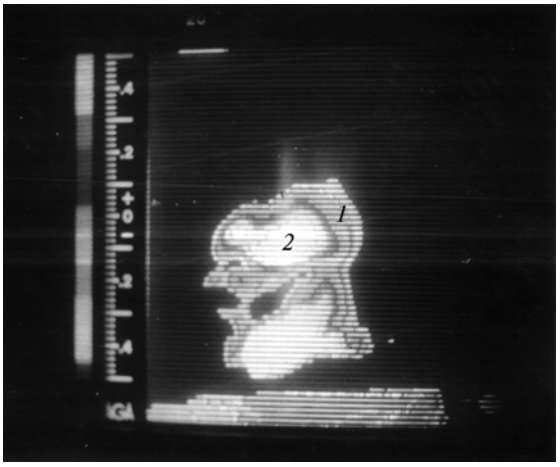

FIG. 3. Thermogram of the dust–gas cloud 30 s *after the start of combustion process.*

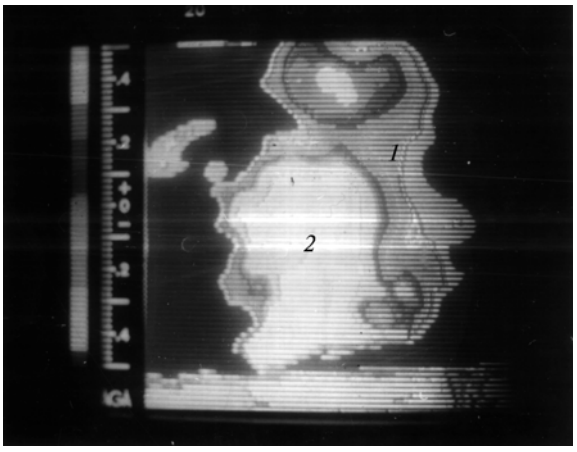

FIG. 4. Thermogram of the dust–gas cloud 60 s *after the start of combustion process.*

The temperature field of the cloud was smoothed (zone *1* had a temperature of about 100°C). The

central part of the cloud (zone *2*) was heated up to 120°C.

Two minutes after the start of the combustion process the cloud spread outside of the field of view of the thermal imaging system and its temperature approached the temperature of the surrounding air. The most part of the cloud had a temperature of 50°C and its small regions had a temperature of 70°C. Three minutes after the start of the combustion process the cloud temperature was no different from the background air temperature.

The techniques developed in the present paper and the results of measurements indicate that these techniques and systems can be used successfully to obtain the information about the ecological situation in the sites of utilization of an industrial waste.

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