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LABORATORY INVESTIGATIONS OF THE COMPOSITION AND DETERMINATION OF THE COEFFICIENTS OF EMISSION OF THE PRODUCTS OF BURNING OF FOREST MATERIALS

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A laboratory setup for physical modeling of forest fires and investigation of the physicochemical characteristics of the process of burning of forest combustible materials (FCMs) has been described. The results of spectrophotometric investigation of the process of generation of pollutants in burning of FCMs have been given. The coefficients of emission of pollutants in burning of cedar fall have been determined.

The increase observed in recent years in the anthropogenic load on forest biocenoses has led to a growth in the number of forest fires. Each new fire-hazard season brings increasingly new examples of forest fires with disastrous consequences for all of Siberia. This includes the Irkutsk, Yakutsk, Kemerovo, Tomsk, and Chita Regions and the Krasnoyarsk, Khabarovsk, and Altai Territories. Vast reserves of industrial wood die in the country each year; products of burning escape into the atmosphere, contaminating it.

In 1997, the Ministry of Ecology of Russia approved and distributed a procedure for calculation of the emissions of pollutants from forest fires [1], which had been developed at Tomsk State University. The procedure, which is based on a mathematical model of forest fires [2, 3], sets forth general requirements on calculation of the emissions of gaseous and dispersed pollutants into the atmosphere in uncontrolled burning of FCMs in forest fires of different types: ground, crown, and subsurface (peaty) ones. The procedure seeks to calculate the final and running values of the amount of the emissions of pollutants and heat into the atmosphere. In creating it, we used numerical values of the coefficients of emission (generation) of pollutants, obtained by different authors [4, 10] on the basis of laboratory experiments and an analysis of the consequences of actual fires. The values of the emission coefficients differ significantly, as a rule. Therefore, the investigations of the emission of pollutants in burning of FCMs carried out in this work were aimed at checking and refining the emission coefficients used in the procedure.

Experimental Bench for Laboratory Investigations of Ground Forest Fires. To model ground forest fires we developed and manufactured a bench (Fig. 1) placed in the large aerosol chamber of the Institute of Optics of the Atmosphere of the Siberian Branch of the Russian Academy of Sciences (Tomsk).

Structurally, the aerosol chamber represents a horizontally arranged cylindrical stainless-steel tank with the entrance port in the end wall [11]. The chamber is airtight and heat-insulated; the interior surfaces are blackened; two air ducts of diameter 600 mm equipped with shutters are made in the upper part of the chamber for natural ventilation and release of pressure. The chamber is fitted with lines and devices for pumping and evacuation of air and for supply of water and vapor and with pressure transducers and temperature sensors connected with the common control desk.

Figure 2 gives a diagram of equipment with which the bench for laboratory investigations of the physicochemical characteristics of the process of burning of FCMs and a convective column above fire is fitted.

On the bench, we carry out the following investigations with different kinds of FCMs depending on their moisture content and supply and on the wind velocity and the slope of the underlying surface to the horizon:

(1) the space-time characteristics of distribution of the radiation temperature of the flame (dispersions, correlation functions, space and time spectra);

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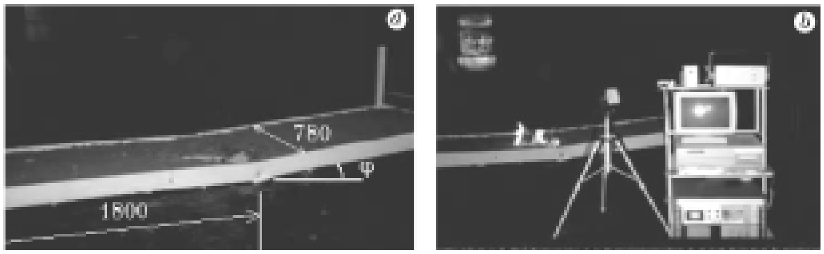

Fig. 1. Bench for modeling of ground forest fires: the proving-ground table (a) and the IR-imaging system and the proving-ground table in the large aerosol chamber (b).

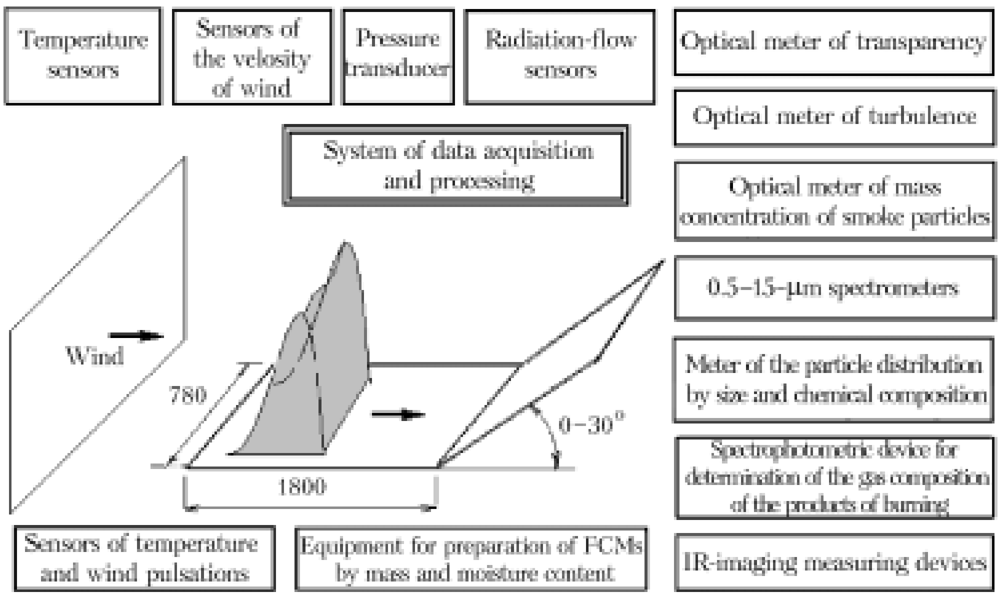

Fig. 2. Devices of the bench for physical modeling of ground forest fires.

(2) the parameters of propagation of fire at the stages of occurrence, development, and suppression with FCMs of different kinds and humidity: the velocity of motion of the front and its width and height, the burning area, the radiation and thermodynamic temperatures, and time fluctuations of all parameters;

(3) the dynamics of density and spectral composition of radiation in the range 0.4–1.2 μm and its difference from the law of black-body radiation;

(4) the number, concentration, and size distribution of aerosol (smoke) particles and the chemical composition of particles;

(5) the transparency of a medium at the site of burning in certain spectral intervals (in the visible and IR ranges);

(6) the limiting conditions of firing and burning as far as the humidity and supply of a fuel material are concerned and the rate of drying of the material by the radiation of the flame;

(7) the chemical composition and concentration of the basic gases released in burning of FCMs;

(8) the velocities of air flows and the turbulent characteristics of a medium in the regions of burning and the convective column;

(9) the pressure at the site of fire and low-frequency and intrasonic pressure oscillations;

(10) crossing the guard bands by the fire.

Description of the Spectrophotometric Method. A spectrophotometric gas analyzer for determination of the content of greenhouse gases in the IR range in atmospheric air and for prompt qualitative and quantitative analyses and dynamic monitoring of the concentration of gas components in the process of technological cycles has been devel-

Fig. 3. Spectrophotometric gas analyzer.

oped at the Institute of Optics of the Atmosphere of the Siberian Branch of the Russian Academy of Sciences. Figure 3 shows the exterior view of the spectrophotometric gas analyzer.

As is well known [12], the absorption of optical radiation by a substance in the linear case is described by the Bouguer–Lambert law:

$$I(\lambda) = I_0(\lambda) \exp [-K(\lambda)L] ,$$

which relates the intensity of the radiation $I(\lambda)$ at the exit of the absorbing medium of length L and the spectral coefficient of absorption $K(\lambda)$ to the intensity of light incident on the medium $I_0(\lambda)$. The parameters $I(\lambda)$ and $I_0(\lambda)$ can be obtained from experiment, after which we can determine $K(\lambda)$ and find the concentration of the gas.

The device represents a fast-scanning IR spectrophotometer with recording and processing of the spectral signal on a personal computer. The absorption spectrum recorded is compared to the absorption spectra of standard specimens that have been put into the database of the computer and then is analyzed with the use of original software. The spectral range $\Delta\lambda$ of operation of the device is 1000–4500 nm. The time of scanning and processing of one realization of the spectrum is 0.5–1 sec, the photometric transmission sensitivity (for L = 2.175 m and 1000 realizations of the spectrum) is up to $5 \cdot 10^{-7}$, and the spectral resolution is 10 cm^{-1}. Preliminary experiments have shown that the spectrum analyzer (over a period of 1 to 5 min) reliably records the basic greenhouse gases, such as water, carbon monoxide and dioxide, and methane, at a level of 0.3–0.5 ppm (the background content of methane in the atmosphere is 1.7 ppm), acetylene at a level of 0.5–1 ppm, and the total content of volatile fractions of light hydrocarbons at a level of 1–2 pp.

The high sensitivity of measurements and the promptness of the spectrophotometer make it possible to simultaneously determine the concentration of a few gases. This enables one to efficiently use the gas analyzer for investigation and monitoring of the products of pyrolysis and burning of forest materials.

Experimental Results and Their Analysis. With the spectrophotometer, we recorded the spectra of the products of burning of the fall of cedar needles with a moisture content of $W \approx 1\%$ in combustion of five 0.4-kg samples with an interval of 30 min and in intake of the gas from the flame at different levels of height. The experiments were carried out in physical modeling of ground forest fires on the bench located in the large aerosol chamber at an ambient temperature of 292 K and a humidity of 60%, and with a slight natural ventilation through the hole in the chamber's upper part. The optical path of the spectrophotometer was L = 0.825 m and the spectral range was 1900–3800 nm. The background signal of the radiator $I_0(\lambda)$ was recorded in a nitrogen atmosphere. We carried out measurements with accumulation of over 100 spectra. The absorption spectra in the IR range selected in both the upper part of the flame, above the glow zone (region I), and the lower part, in the immediate vicinity of the flame front — $(1–2) \cdot 10^{-2}$ m above the FCM layer (region II), are mainly determined by a steam, carbon monoxide and dioxide, methane, and a set of unidentified hydrocarbons. Figure 4 gives two fragments of the absorption spectra of the products of burning of cedar-needle fall in intake of the gas for analysis in regions I and II, whereas Table 1 gives data on the concentration of individual gases in parts per million (ppm).

The experimental procedure in [13] involved recording of the background content of CO_2, CH_4, CO, H_2O, C_2H_2, and C_xH_y in the large aerosol chamber throughout the measurement cycle. The measurements were carried out after the complete combustion of each of the five FCM samples. The measurement results are given in Fig. 5. The burnt-sample Nos. i (i = 5) are plotted on the abscissa axes, whereas the ordinates correspond to the concentration of

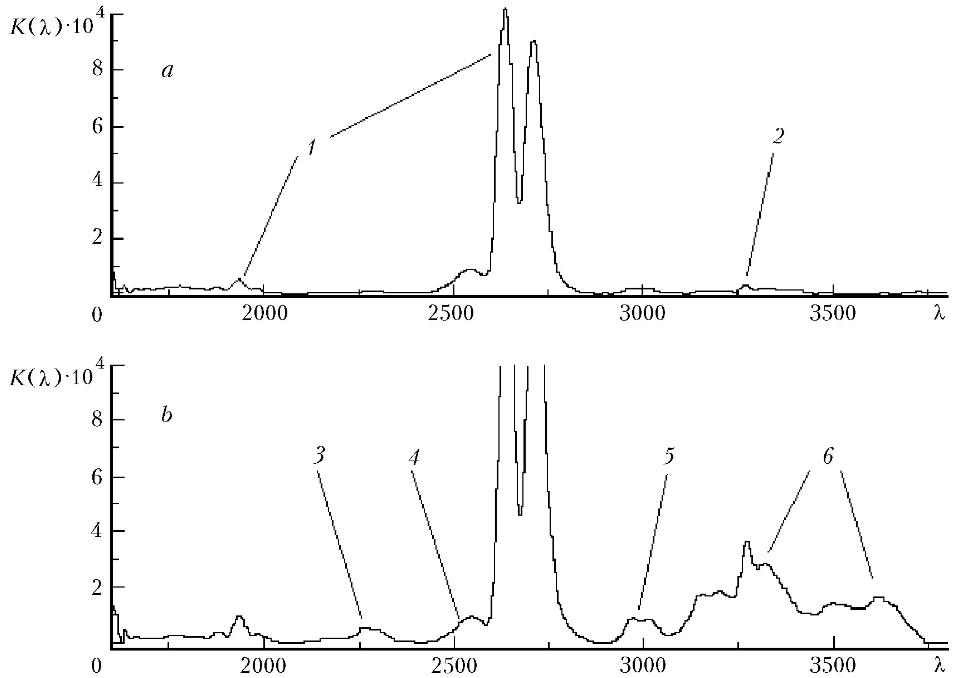

Fig. 4. Fragments of the absorption spectra of the products of burning of cedar-needles fall in regions I (a) and II (b): 1) carbon dioxide; 2) methane; 3) carbon monoxide; 4) water; 5) acetylene; 6) unidentified hydrocarbons C_xH_y. $K(\lambda)$, cm^{-1}; λ, nm.

TABLE 1. Qualitative and Quantitative Compositions of the Products of Burning of FCMs

Region	CO_2	CH_4	CO	H_2O	C_2H_2	ΣC_xH_y
I	6750	384	576	20550	85	625
II	6660	49	110	19150	4	73

TABLE 2. Coefficients of Emission of the Products of Burning of Cedar Fall with a Moisture Content of 1%

Pollutant	CO_2	CH_4	CO	H_2O	C_2H_2	C_xH_y
μ_n	44	16	28	18	26	≈30
$\overline{C}_n$, ppm	90.0	2.8	5.3	1280.0	4.1	4.6
K_n, kg/kg	0.920	0.010	0.034	5.354	0.025	0.042

the products of burning C_n in ppm, where n = 1 is carbon dioxide, 2 is methane, 3 is carbon monoxide, 4 is water, 5 is acetylene, and 6 is unidentified carbons C_xH_y.

From the results of the investigations, we calculated the emission coefficients K_n of the products of burning of cedar fall:

$$K_n = \frac{7.43 \cdot 10^{-5}\, \mu_n \overline{C}_n}{M_0\,(1 - K_{\text{inc}})};$$

here M_0 is the mass of the weighed sample, equal to 0.4 kg, and $K_{\text{inc}} = M_{\text{inc}}/M_0$ is the coefficient of incomplete combustion of FCMs, equal to 0.2. A numerical coefficient of $7.43 \cdot 10^{-5}$ sets up a correspondence between the molar and weight concentrations of the substances under study in the large aerosol chamber with known volume and temperature of the medium.

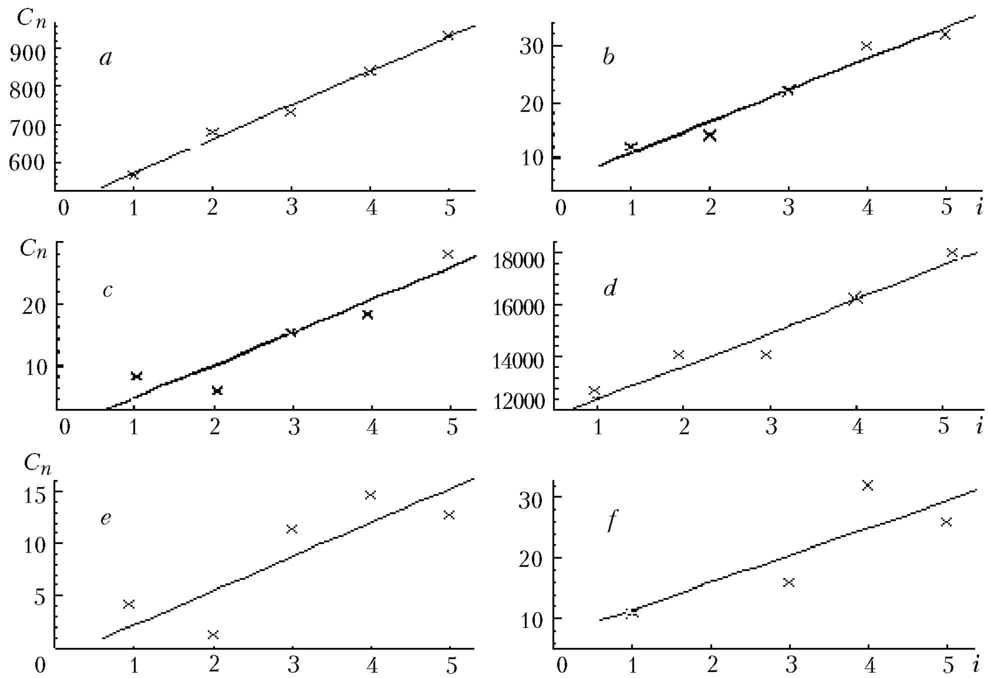

Fig. 5. Concentration of the products of burning of FCMs in the large aerosol chamber vs. number of the burned weighed samples of cedar-needle fall: a) carbon dioxide, Sq_1 = 17 and $\overline{C}_1$ = 90; b) methane, Sq_2 = 1.1 and $\overline{C}_2$ = 2.8; c) carbon monoxide, Sq_3 = 3.3 and $\overline{C}_3$ = 5.3; d) water, Sq_4 = 467,and $\overline{C}_4$ = 1280; e) acetylene, Sq_5 = 4.5 and $\overline{C}_5$ = 4.1; f) unidentified hydrocarbons C_xH_y, Sq_6 = 5.2 and $\overline{C}_6$ = 4.6. C_n, ppm.

The results of the calculation of the emission coefficients of the products of burning of cedar fall are given in Table 2.

The accuracy of the procedure of determination of the emission coefficients of pollutants was evaluated by comparison to the emission coefficients obtained by other methods. A procedure (based on the optoacoustic method) of determination of the emission coefficients of a carbonic acid gas was proposed in [14]. In this procedure, the coefficients of emission of a carbonic acid gas in burning of the falls of cedar, larch, and pine, living needles of cedar, spruce, and fir, and Cladonia lichen and Schreber's moss were determined. The coefficients of emission of carbon dioxide in burning of the cedar fall was 0.973. The values of the emission coefficients of the carbonic acid gas, obtained by the optoacoustic and spectrophotometric methods, show a good agreement, which confirms the reliability of the results.

Thus, our investigations of the process of generation of pollutants in burning of cedar-needles fall have enabled us to determine the emission coefficients of the basic pollutants with a satisfactory degree of accuracy and have shown that such investigations must be carried out for different FCM types characteristic of forest-covered areas of the country.

NOTATION

C_n, concentration of the products of burning, ppm; $\overline{C}_n$, average increase in the concentration of the nth pollutant in combustion of one FCM sample, ppm; $I(\lambda)$, intensity of the medium's radiation, W/m^2; $I_0(\lambda)$, intensity of light incident on the medium, W/m^2; $K(\lambda)$, spectral coefficient of absorption, cm^{-1}; K_{inc}, dimensionless coefficient of incomplete combustion; K_n, emission coefficient of the nth pollutant, kg/kg; L, optical path of the spectrophotometer, m; M_0, mass of the weighed sample of forest material, kg; M_{inc}, mass of unburned forest material (mass of incomplete combustion), kg; Sq_n, standard deviation of the measured concentrations of the nth pollutant, ppm; W, moisture content of FCMs, wt.%; $\Delta\lambda$, spectral range of operation of the spectrophotometer, nm; λ, radiation wavelength, nm; μ_n, dimensionless relative molecular weight of the gas (of the *n*th pollutant). Subscripts: inc, incomplete combustion; *i*, experiment No.; *n*, type of pollutant; *x* and *y*, number of carbon and hydrogen atoms in the molecules of unidentified hydrocarbons; 0, initial value of the FCM mass in the experiments.

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