ON POTENTIAL OF PASSIVE REMOTE TECHNIQUE FOR A QUANTITATIVE ANALYSIS OF THE GAS COMPOSITION OF INDUSTRIAL EMISSIONS

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A simple gas–analyzer operation has been modeled in the paper based on the recorded spectral behavior of radiation pattern of heated gases of industrial origin. The emissivities of gases have been directly calculated using the parameters of vibrational–rotational lines of radiating gases identified by our own methods. Amplitude of received signals as a function of spectral region, temperature, background radiation, and recording system parameters has been analyzed. The optimum parameters of the analyzer have been chosen when registering SO_2 *as an example.*

INTRODUCTION

Active techniques for remote sounding of gaseous industrial emissions to measure the concentration of pollutants are most developed now. In this case gas cloud is exposed to the radiation of laser or some other source, and the parameters of radiation are then measured, associated with interaction effects such as absorption or Raman scattering. However, equipment for such measurements must include a source of radiation with a power supply unit and an instrument module to monitor the radiation parameters. This leads to additional problems in the development and realization of hardware as well as in extraction of useful information from received signal.

A proposed analyzer of concentration of harmful gases in industrial emissions, based on detection of self–radiation of the examined gas, is free from these drawbacks.

CALCULATION OF ANALYZER CHARACTERISTICS

Depicted in Fig. 1 is the block diagram of a proposed portable setup intended to measure the concentration of harmful gases.

A cloud of gas heated up to ≅ 1000 K and emitted from a stack is a source of radiation. The radiation propagating in all directions falls on a recording system, which includes a set of light filters, a receiving mirror of parabolic type with Cassegrainian reflector, a photodetector, and an electronic unit for amplification, recording, and processing of measurement results.

The incoming radiant power on the detector is defined as[1]

$$I_{in} = I_{em}\, \mathrm{p} D_m^2 T_{atm}\, \eta_{opt}\, 4L^2 , \qquad (1)$$

where I_{in} is the incoming radiant power, I_{em} is the radiant power emitted from the surface of the gas cloud, D_m is the diameter of a mirror of the receiving system, η_{opt} is the attenuation due to optical system (light filters), T_{atm} specifies the losses due to atmosphere on the path, and L is the path length (the distance from the source to the receiver).

It follows from Eq. (1) that we must evaluate first the emitted radiant power and then its attenuation due to atmosphere and optical system.

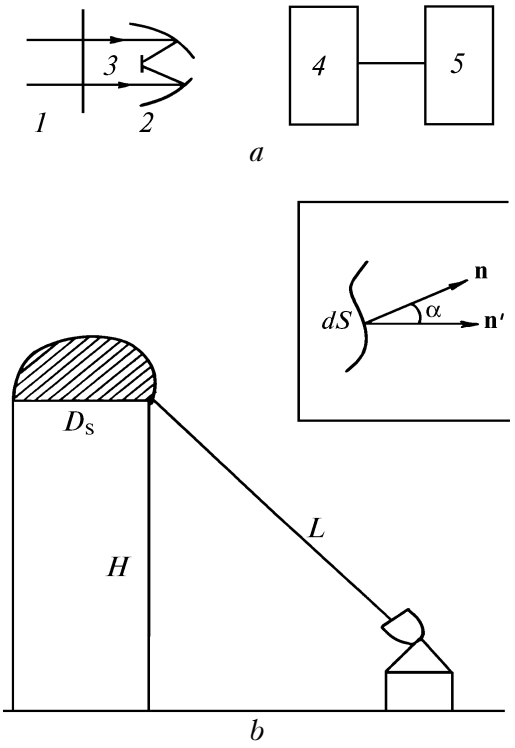

FIG. 1. Block diagram of radiation analyzer (a) and scheme of recording of radiation emitted by a gas cloud (b): light filter (1), telescopic receiving mirror (2), photodetector (3), preamplifier (4), and unit for signal processing and recording (5). Here H is the stack height, D_s *is the stack diameter, and L is the path length. (Depicted in fragment is the geometry of propagation of radiation emitted by the gas cloud.)*

1. Calculation of radiant power emitted by a heated gas

In the design of a remote gas analyzer we assume that the surface of a gas cloud is the emitting source. The radiation propagates uniformly in all directions due to

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chaotic arrangement of radiating gas molecules in space. Radiant power outcoming from the element of area dS in **n'** direction (fragment in Fig. 1) is

$$dI = I_0 \cos\alpha \, dS \, , \qquad (2)$$

where I_0 is the radiant power along the normal **n'** to the element of area dS, α is the angle between **n** and **n'**, and **n'** specifies the direction toward the receiver.

Radiant power emitted by the surface area S in **n'** direction is determined by integrating over dS

$$I = I_0 \int\limits_S \cos\alpha \, \mathrm{d}S = I_0 S_0 \, , \qquad (3)$$

where S_0 is the projection of S on the plane to which **n'** is the normal.

For our configuration the parabolic mirror serves as a receiving system and cuts out the paraxial beam with the cross sectional area $S_0 = \pi D_m^2/4$ from whole radiant flux, and obviously the cross section of this beam is S_0. Consequently, we can suppose that the amplitude of signal incoming to the detector is independent of the configuration of the emitting surface. Let us now evaluate the radiant power I_0 emitted by the surface of a gas cloud. In so doing the radiation is assumed to be diffuse and the condition of thermodynamic equilibrium (TE) is accepted for the emitting volume (violation of TE is beyond the scope of the present paper). Then the flux emitted in the spectral range $[\nu_1, \nu_2]$ in the direction normal to the surface of the emitting volume within unit solid angle is

$$I = I_0 \int B(\nu, T) \, E_m(T) \, \mathrm{d}\nu \, ,$$

where $B(\nu, T)$ is the Planck function,[2] and $E_m(T)$ is the emissivity of heated air mixture.

In TE approximation, the emissivity is determined as

$$E_m(T) = 1 - \exp(- K_m(T) \, \rho\chi) \, , \qquad (4)$$

where K_m is the spectral absorptance of a medium, ρ is the gas concentration, χ is the length of gas volume emitting in the direction x. In our case the stack diameter can be taken as χ.

To calculate the absorptance, the temperature of the gas cloud must be known. The temperature can be found by the following ways:

1) by measuring the total radiant flux in the optical range $I_{total} = \sigma T^4$, where σ is the Boltzmann constant;

2) by direct measurement with contact temperature gauge;

3) by taking the value of T corresponding to the production process chart.

The most accurate values of absorptance are found by direct calculations on the basis of the spectral line parameters corresponding to a specific temperature.[3] The technique for calculation of the parameters of rotational–vibrational lines of gases heated up to 300–2000 K was elaborated by one of the authors and was evaluated for gaseous products of combustion.[4–7]

PROPAGATION OF RADIATION FROM A GAS CLOUD THROUGH THE ATMOSPHERE AND ACCOUNT OF THE BACKGROUND ILLUMINATION

In general the complete radiation transfer equation (3) should be solved. However, the introduction of acceptable simplifications (consideration of stationary case, disregard for scattered radiation, because the emitting gas volume can be considered as isolated gaseous emitter) allows the use of more simple relation for radiant intensity

$$I_m(L) = I_{m0} \exp[- \int\limits_{L_1}^{L_2} K_m(l) \, \mathrm{d}l] \, , \qquad (5)$$

where L_1 and L_2 are distances to the end points of the path, and $K_m(l)$ is the absorptance of the atmosphere on the entire path length from the source to the receiver. The use of spectral ranges referred to as the atmospheric windows is most advantageous, because the atmospheric effect can be neglected for short paths.

The radiation from the sun, the sky, and the Earth[8,9] causes the background illumination. The radiation from the sun is equivalent to that from a complete radiator at $T = 5600$ K; the radiation from the sky is due to scattered solar radiation with maximum at $\lambda = 0.5$ μm. The Earth's radiation has a maximum centered at 9.6 μm. The background illumination can be taken into account when choosing the operational wavelength range. It is feasible by measuring at viewing angles different from that of the source of emission and by subsequent subtraction of the "zeroth" radiant energy from the source–directed measurements.

CHOICE OF OPTIMUM CHARACTERISTICS OF ANALYZER USING THE PROBLEM OF DETERMINATION OF SO_2 CONCENTRATION AS AN EXAMPLE

Based on the above–mentioned, let us consider an analyzer developed for the detection of SO_2–bearing emissions, for example, from copper works.

According to Ref. 10, the maximum instantaneous permissible concentration of SO_2 in individual emission is $\rho SO_{2\,inst} = 1.88 \cdot 10^{-7}$ atm , while the average daily maximum permissible concentration is $\rho SO_{2\,av} = 1.88 \cdot 10^{-8}$ atm.

The maximum diameter of a stack D_s is taken to be 1000 cm. Because in the chosen spectral range $K_m = 12$ atm·cm, $\alpha = K_m \rho SO_2 D_s \cong 2 \cdot 10^{-4}$. It determines the thickness of the optical emitting layer. For such α, we can restrict ourselves to consideration of only linear term in the expansion of the exponential function in Eq. (4). Finally, the relation for emissivity can be written as follows:

$$E_m = K_m \, \rho SO_2 \, D_s \, .$$

Then ρSO_2 can be found directly from the emissivity E_m measured in the given spectral range.

Results of our calculation agree with the experimental data[11] on the absorptance of SO_2 heated up to $T = 500$ K within the experimental error (see Fig. 2).

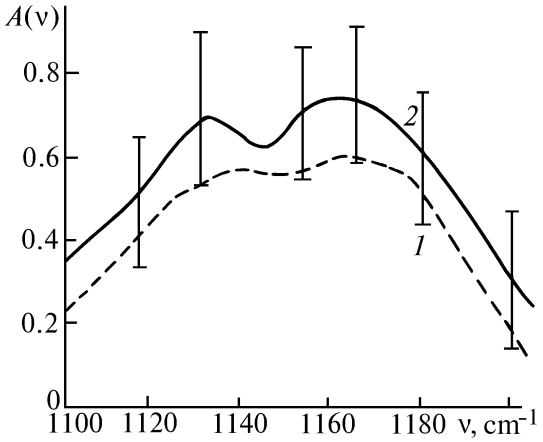

FIG. 2. The calculated absorption function of SO_2 *heated up to* 500 K *(1) as compared to the experimental one* [1,2] *(2).*

Calculation of spectral dependence of emissivity integral confirms the information content of chosen spectral range centered at 8.9 μm (Fig. 3), because the behavior of this dependence is completely determined by spectral dependence of SO_2 radiation, whereas the Planck function varies only slightly in the chosen spectral range (8.6–9.3 μm). Calculations of the dependence of emissivity integral on the mirror diameter, observation angle, and temperature range allow the optimum design characteristics of the analyzer to be found. However, with increasing SO_2 concentration, when the exponent in Eq. (4) becomes large, the error in determining the SO_2 concentration also increases, and there exists the limiting value of $K_m(T)\rho\chi$, at which the error $\Delta\rho$ becomes greater than allowable one. In our example, for a given error $\Delta\rho$ of 10% this value is equal to approximately 2.5 atm·cm, what is many times higher than the maximum permissible concentration (MPC).

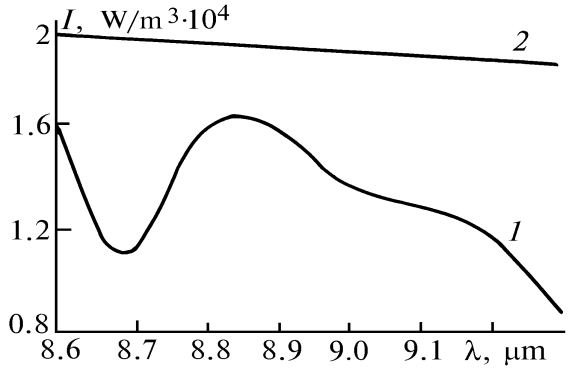

FIG. 3. Spectral dependence of the SO_2 *emissivity integral (1) and the Planck function (2) (*T = 1000 K *).*

CHOICE OF BANDWIDTH OF A LIGHT FILTER

The role of instrumental function should be analyzed in the design of the device. Obviously, some optimum value $\Delta\nu$, determined individually for each spectral range and examined gas, should exist, which would provide a maximum amount of radiation incoming to the receiver. This stage is very important, because the bandwidth of a light filter is practically specified. The wavelength is chosen, which corresponds to the maximum of spectral radiant power (center of vibrational band). The radiant intensity is then calculated via the instrumental function bandwidth. Depicted in Fig. 4 is the result of calculation at T = 1000 K and optical thickness of about 5 atm·cm. Maximum values of I_{em} and I_{in} are achieved at $\Delta\nu$ = 0.025 μm. Instrumental function smoothes out the signal, and the recorded flux grows as long as the radiation bandwidth is narrower than that of the instrumental function.

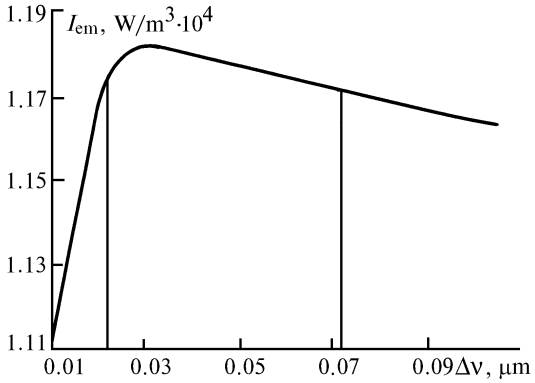

FIG. 4. SO_2 *emissivity integral against instrumental function half–width.*

Because the spectral range 8–12 μm, chosen as operational one, refers to the atmospheric windows, the atmospheric absorption is negligible for the path lengths considered here (up to 1 km). However, in general the atmospheric transmission function must be evaluated rather accurately.

RECORDING OF RADIATION

The photodetectors (PDs) should be used as receivers of radiation. Their type is determined, in addition to the other parameters, by their sensitivity and consequently by the diameter of a receiving mirror. Because the cost of a mirror is proportional to its diameter, it is advantageous to choose the smallest diameter with PD sensitivity sufficient for consistent recording of a signal. Thermal receivers operating under room temperature are most convenient for use, but they possess a low sensitivity and their application is advantageous only to monitor the excess of maximum instantaneous permissible concentration of emission. At the same time, their application to measuring the gas concentration less than MPC is ineffective. The photoelectric semiconductor detectors are more promising for this aim.[12]

CONCLUSION

The principal feasibility of development of small portable sensors of concentration of harmful gases in heated emissions from industrial objects on the basis of passive remote methods of radiation recording has been demonstrated in the present paper. We have sought to call attention of the developers of the device to the advisability of developing such devices promising for ecological monitoring of emissions of pollutants.

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