A method for laser measurement of disperse composition and concentration of aerosol particles

Olga B. Kudryashova, Igor R. Akhmadeev, Anatoly A. Pavlenko, Vladimir A. Arkhipov,
Sergey S. Bondarchuk

Institute for Problems of Chemical & Energetic Technologies (IPCET)
Siberian Branch of the Russian Academy of Sciences (SB RAS)
Sotsialisticheskaya Str., 1, 659322 Biysk, Russia
Tel.: + 7 [3854] 30-48-69 Fax: +7 [3854] 31-13-09 E-mail: olgakudr@inbox.ru

Abstract

A modified method of small-angle scattering that consists in solving a series of direct problems in aerosol optics is proposed to obtain a function of particle size distribution. A modified method of spectral transparency is employed to determine the concentration of particles in a cloud. A measurement system comprising radiator (helium-neon laser), photodetector and recording instruments have been developed. Measurements in aerosol clouds are performed.

Keywords: Size distribution, particle concentration, methods of small-angle scattering, methods of spectral transparency

1. Introduction

When studying combustion processes, as well as for the purpose of environmental monitoring, one of the important problems is the measurement of disperse composition and concentration of combustion product particles which present, generally, a two-phase flow. To measure particle size spectrum and particle concentration in aerosols, noncontact optical methods are widely used. The advantage of optical methods consists in the fact that they do not introduce aerodynamic distortions and allow conducting continuous measurements with quite a satisfactory accuracy.

In the present paper the determination of a function of size distribution of two-phase medium particles is based on the modified method of small-angle scattering [1, 2]. For determination of particle concentration we have used the modified method of spectral transparency [3]. The measurements are performed using a specially developed hardware and software system.

2. Method of measurements

Figure 1 shows a model based on the theory of radiation transfer in the form of narrow collimated laser beam through fog, clouds and other highly scattering media, particularly, scatterings at small angles.

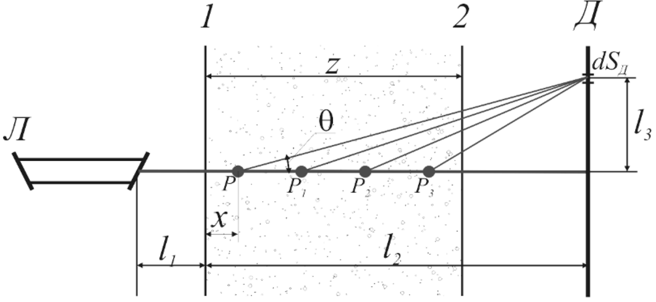


Fig. 1. Diagram of laser beam scattering in an aerosol layer.

The laser beam *Л* propagates through a scattering layer with boundaries “1” and “2”, producing some illuminance on the plane *Д*. A distance from the laser to the first boundary is equal to l_1. Particles of an aerosol cloud, which are present in the beam, scatter radiation. As a result, irradiance of the plane *Д* will be characterized not only by a direct beam attenuated due to absorption and scattering, but also by radiation scattered from the particles.

Under the assumption of uniformity of concentration and size distribution of particles in an aerosol cloud, an equation for scattered radiation flux coming onto the plane *Д* is as follows:

$$I(y)=\frac{\pi S C_n}{4}\int_0^z \left[I_0(x)B(x,y)F(x)\right]dx, \tag{1}$$

wherein $F(x)=\int_0^\infty Q_S\left(D,\Theta(x)\right)D^2 f(D)dD$; $I_0(x)=I_0\exp\left[-C_n x Q_{осл}\right]$ – intensity of radiation falling into x point; C_n – counting concentration of particles; x – distance from the boundary l of a scattering layer to the point P; $Q_{осл}$ – attenuation coefficient. The radiation scattered from a single particle for the region of small angles θ, under the assumption of sphericity of the particles, is defined in the form of analytic dependence presented below:

$$Q_S(\rho,\theta)=\frac{\rho^2}{4\pi}\cdot\left[\frac{2J_1(\theta\rho)}{\theta\rho}\right]^2,$$

wherein $\rho=\frac{\pi D}{\lambda}$ – diffraction parameter (Mie’s parameter); θ – radiation scattering angle; D – diameter of a particle; λ – wavelength of probe radiation; $J_1(\theta\rho)$ – first-order Bessel function of the first kind.

The multiplier $B(x)$ that takes into account the attenuation of scattered radiation under the Bouguer law is defined by the following relation:

$$B(x,y)=\exp\left[-C_n Q_{осл}\frac{z-x}{\cos\Theta(x,y)}\right],$$

wherein $\Theta(x,y)=arctg\left(y/(l_2-x)\right)=arctg\left(l_3/(l_2-x)\right)$.

At greater values of τ (>0.15) it is necessary to introduce the corresponding corrections into the expression for complete indicatrix of scattering on the plane *Д*:

$$I_{пол}(y)=\frac{\pi S C_n}{4}\int_0^z\left[I_0(x)B(x,y)F(x)\left[\frac{1}{1-\Delta(\tau(z),\Theta(x,y))}\right]\right]dx. \tag{2}$$

The essence of the method consists in finding the spectrum of aerosol particle sizes using the measured small-angle indicatrix of scattering by comparing it with a series of computational indicatrixes of scattering found by formulae (1), or with consideration of multiple scattering at τ >0.15 (2). Each computational indicatrix of scattering is calculated along with its proper distribution function.

Gamma distribution is accepted as a basic function of distribution:

$$f(D)=aD^{\alpha}e^{-bD},$$

wherein $a>0$ – normalizing factor; α, b – distribution parameters; D – diameter of a particle.

The determination of $f(D)$ using the measured indicatrix of scattering $I_e(y)$ reduces to enumeration of distribution parameters $\{\alpha, b\}$ and calculation of the functional:

$$\Omega=\min_{\alpha,b}\left\{\sum_{i=1}^{n}\left|I_e(y_i)-I(y_i)\right|\right\},$$

wherein $I_e(y_i)$ ($i=1,2,\ldots,n$) – measured values of indicatrix of scattering for discrete values on the plane *Д* y_i; $I(y_i)$ – values calculated by (1), or (2) at τ >0.15.

Besides the function of distribution, averaged characteristics defined by the formula below are used to describe dispersive media:

$$D_{mn} = \left[\int_0^\infty D^m f(D)\,dD \Big/ \int_0^\infty D^n f(D)\,dD \right]^{\frac{1}{m-n}}, \tag{3}$$

wherein *m*, *n* – integral numbers that imply the order of distribution function moment.

The most widespread are the following characteristic dimensions: D_{10} – arithmetical mean; D_{20} – mean-square; D_{30} – volume-averaged; D_{32} – mean surface-volumetric; D_{43} – mass-averaged.

The method considered above allows determining the function of particle size distribution $f(D)$. Methods for determining the concentration of particles are based on the measurement of spectral coefficients of two-phase flow transmission for a fixed wavelength λ of the probe radiation.

The basic equation of the spectral transparency method is an expression for optical density of the layer of uniformly distributed polydisperse particles:

$$\tau = \ln(1/T) = \frac{1.5 C_m \cdot l \cdot \bar{Q}(\lambda)}{\rho_k \cdot D_{32}},$$

wherein $T = I_0 / I_0'$ – transmission coefficient; ρ_k – density of particles material; l – optical length of probe; D_{32} – mean surface-volumetric diameter of particles; C_m – mass concentration of particles; $\bar{Q}$ – averaged factor of attenuation efficiency.

Thus, from the experimentally measured *T* and value D_{32} calculated by formula (3), the concentration of particles in the measurement zone is determined as follows:

$$C_m = \frac{\tau_\lambda \cdot \rho_\kappa \cdot D_{32}}{1.5 \cdot l \cdot \bar{Q}(\lambda)}.$$

3. Measurement system

The system is composed of the following instruments and devices:

- measuring chamber (1 m^3 in volume);
- radiation source: a helium-neon laser *HRP050* with a wavelength of 0.632 μm and 5 mW power, or 12 mW power *HRP120*;
- recording unit consisting of 8 photodiodes of S1337-1010BR type (manufactured by *HAMAMATSU PHOTOTONICS*) installed on the same substrate;
- measuring 8-channel amplifier of *У-8* brand;
- ADC *L783* manufactured by *L-Card* and a PC;
- software designed for recording and processing measurement information to determine the counting and mass function of particle size distribution, mean surface-volumetric diameter, and concentration of aerosol particles.

The measured data recording frequency is 100 kHz.

Computational parameters read-out time is between 10 and 120 seconds.

The laser radiation is oriented at an angle of 90° towards one of the faces of the measuring volume, modulated with a frequency of 80 Hz, and directed through a scattering medium (Fig. 2). The optical radiation flux scattered at different angles is recorded by the photodiode bar located in the plane perpendicular to the laser beam. The photodiode bar permits recording the scattered radiation at an angle between 0.3 and 20° relative to the laser beam. For the wavelength of 0.632 μm, silicon photodiodes *S1337-1010BR*, manufactured by *HAMAMATSU PHOTOTONICS*, with a sensitive platform of about 100 mm^2 were used.

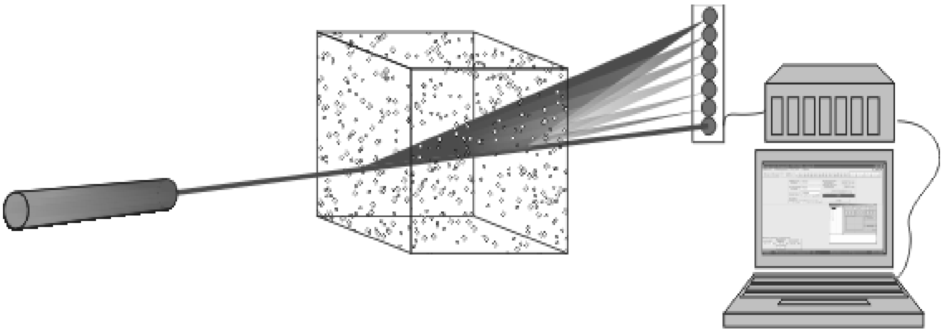
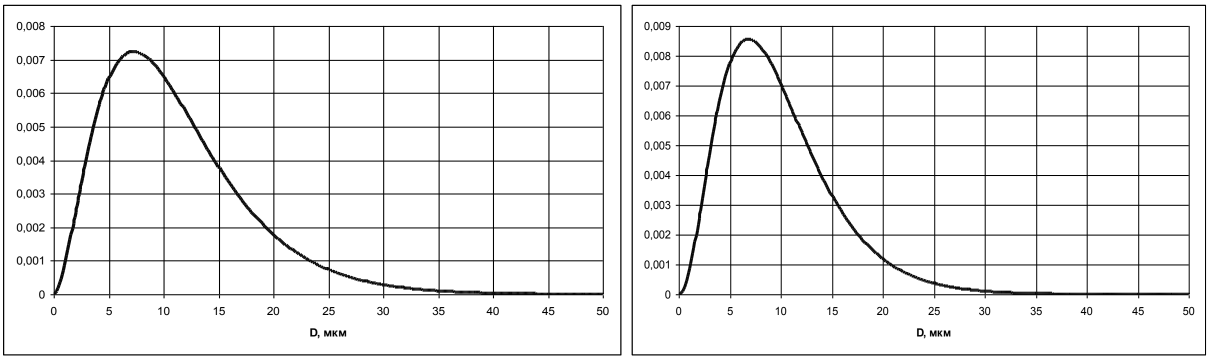


Fig. 2. Scheme of the setup.

To design the photodiode bar, photodiodes similar in sensitivity were used. To allow for deviations of signals level, correction coefficients were introduced for each photodiodes.

4. Measurement results

To test the method proposed, measurements of the function of particle size distribution and concentration for water aerosol, sprayed SiO_2 with a specified dispersity (0.063-1 μm), and aluminum powder ASD-6 were performed. Aerosols were produced by an explosion-type generator in the measuring chamber. The amount of sprayed substance was 3 g for water, 0.21 g for ASD-6 and SiO_2. Figure 3 shows the mass function of distribution of water and SiO_2 particles by size. The parameters of distribution and concentration are presented in Table 1.



a) H_2O b) SiO_2

Fig. 3. Mass function of distribution of aerosol particles.

Table 1. Parameters of the function of particle size distribution and concentration of particles in aerosol.

Substance	α	b	D_{32}, μm	D_{43}, μm	C_m, g/m^3
ASD-6	0.7	0.5	7.5	9.6	0.21
H_2O	0.9	0.25	14.9	18.8	0.29
SiO_2	1.31	0.34	12.8	15.7	0.26

5. Analysis of experimental data

The mass-averaged diameter of ASD-6 particles in aerosol is 9.6 μm and conforms to data obtained by using an optical analyzer PIP 9.1 and to those from literature. The concentration of aluminum particles in a cloud corresponds to the uniform distribution of scattered substance throughout the measuring volume.

The dispersity of sand proved to be higher than initial. It can be explained by the fact that there occurs an additional crushing of SiO_2 particles (more fragile than those of aluminum) when using the explosion spraying method. The concentration of SiO_2 aerosol particles in the experiments is somewhat higher than that case when the particles were distributed uniformly in the measuring volume (0.21 g/m^3). It is explained by the fact that the laser beam passes straight over the generator where the concentration of the substance is higher than in distant parts of the chamber.

As seen from Table 1, the measurements of concentration of sprayed water particles showed that the setup had registered the presence of only about 10% of the initial water mass in the sprayed aerosol. We believe that one of the reasons for such a situation is the limitation of Mie's parameter, $\frac{\pi d}{\lambda} > 1$; thus, the method does not identify submicron size particles at a wavelength of $\lambda = 0.63$ μm. It may be assumed that in explosion spraying there arise particles with sizes of 1 to 100 nm, whereas solid particles having an original particle size of more than 1 μm can be recorded by the setup.

6. Conclusion

The paper proposes a modified method of small-angle scattering to determine parameters of the function of size distribution of aerosol particles, as well as a modified method of spectral transparency to determine the concentration of particles in a cloud. A measurement system to implement the proposed method of measurement has been developed. The measurements performed for model fine-dispersed powders in a cloud, as well as in analysis of dispersity of different water aerosols, have shown that this optical method gives good results if the particles in aerosol have sizes satisfying the condition of $\frac{\pi d}{\lambda} > 1$.

References

1. K.S. Shifrin. *Introduction to Ocean Optics. Leningrad*: Gidrometeoizdant. 1983.
2. I.R. Akhmadeev. *A Modified Method of Small-Angle Scattering to Measure Dispersity of Aerosol Particles.* Proc. of the 5-th All-Russian scientific conference "Basic and Applied Problems of Modern Mechanics", Tomsk: Tomsk University Press. 2006, pp. 55-56.
3. V.E. Zuev, I.E. Naac. *Inverse problems of the laser monitoring of the atmosphere.* Novosibirsk: Nauka. 1982.