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IDENTIFICATION OF SIZE AND CONCENTRATION OF SUBMICRON PARTICLES ON THE BASIS OF RAYLEIGH SCATTERING MODEL

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Abstract. A method of identification of maximum size and concentration of submicron aerosol particles based on measurement of intensity attenuation of a parallel beam of probe optical radiation is described. Offered method makes it possible to determine both particle concentration and maximum particle size with controlled accuracy for aerosol media without any initial information about particle size distribution.

Particle size distribution of aerosol media (in the process of plasma chemical synthesis, preparation of fuel mixtures, analysis of combustion products etc.) laws of formation and its mass-geometry characteristics determine parameters and efficiency of many technology processes [1]. In this case the most accurate methods of study of such objects are non-contact optical methods. An approach making it possible to identify mass concentration and maximum size of condensed particles using the data of laser probing of aerosol formations is presented in this paper. According to offered method of measurement of optical density of dispersed medium measurements are performed in several points of spectral wavelength range: the boundaries of this range are selected on the basis of information about complex refractive index of particle material. When monochromatic radiation with the wavelength λ passes through a layer with the width l of uniformly distributed particles with the diameter D and mass concentration C_m its intensity is attenuated due to scattering and absorption by particles. Spectral transmittance T_λ, associated with Beer–Lambert–Bouguer law [2] is a quantitative characteristic of attenuation.

$$T_\lambda = I_\lambda / I_{0\lambda} = \exp(-\tau_\lambda) \quad (1)$$

where I_λ – radiation flux passed through the layer; $I_{0\lambda}$ – incident radiation flux.

Expression for spectral optical density τ_λ for monodisperse particles in the framework of assumptions of Mie theory has the following form [2]:

$$\tau_\lambda = \frac{1.5 C_m l}{\rho D} Q(\alpha, m) \quad (2)$$

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where ρ – particle material density;

Dependence $Q(\alpha,m)$ of dimensionless attenuation efficiency factor in equation (2) has a complex oscillatory character on diffraction parameter (Mie parameter) $\alpha=(\pi D)/\gamma$, from complex refractive index of particle material $m=n-i\chi$ (n – refractive index; χ – attenuation coefficient) and in common case is calculated using exact formulae of Mie theory.

In case of "small" particles if Rayleigh scattering condition is met $\alpha < 0.2$ attenuation efficiency factor is determined from the following analytical dependence [2]:

$$Q(\alpha,m)=F(m)\cdot\alpha\text{, where}\quad F(m)=\frac{24n\chi}{\left(2+n^2-\chi^2\right)^2+\left(2n\chi\right)^2} \tag{3}$$

After substitution of (3) into the expression for optical density (2) we have the following:

$$\tau_\lambda=\tau_\lambda^{\text{calc}}=\frac{1.5C_m l}{\rho D}\cdot F(m)\frac{\pi D}{\lambda}=\frac{1.5\pi C_m l}{\rho\lambda}F(m) \tag{4}$$

(4) implies that spectral density τ_λ in case of Rayleigh scattering does not depend on particle size D. Therefore, mass particle concentration can be determined from (4) using value of τ_λ:

$$C_m=\frac{\rho\lambda\tau_\lambda}{1.5\pi l F(m)} \tag{5}$$

In case of polydisperse particles, the expression for spectral optical density is determined as [2, 3]:

$$\tau_\lambda=\frac{1.5C_m l}{\rho}\cdot\frac{\int_0^\infty Q(\alpha,m)D^2 f(D)\,dD}{\int_0^\infty D^2 f(D)\,dD} \tag{6}$$

It should be noted that substitution of expression (3) for $Q(\alpha,m)$ in (6) as in case of Rayleigh scattering gives the same expression as (5) for mass concentration of particles.

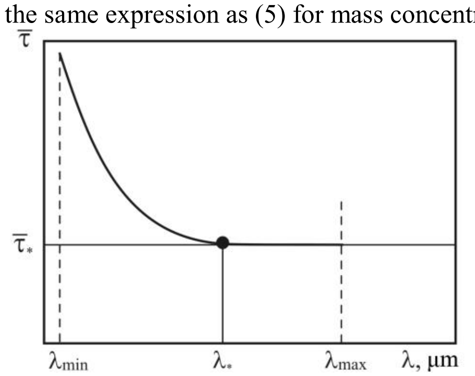

Fig. 1. Caption of the figure 1. Below the figure.

This method of C_m calculation from formula (5) using measured value of τ_λ is considered valid only for a limited range of probe radiation wavelength $\lambda \geq \lambda_*$.

To determine wavelength λ_*, limiting Rayleigh scattering region spectral optical density τ_λ^{meas} is measured in a certain wavelength $\lambda_{min} \le \lambda_* \le \lambda_{max}$ range and from the analysis of function $\bar{\tau}_\lambda = \bar{\tau}_\lambda^{meas} / \bar{\tau}_\lambda^{calc}$ limiting value λ^* is determined. Up to this value $\bar{\tau}_\lambda$ decreases monotonically (fig.1) and then $\bar{\tau}_\lambda = \bar{\tau}_{\lambda_*} = \text{const}$ for $\lambda > \lambda_*$. Particle mass concentration for region $\lambda > \lambda^*$ is determined using formula (5).

In order to calculate D_{max} value using relation given in [2]

$$D_{max} = \frac{\lambda_*}{\pi} \alpha_* (\lambda_*) \tag{7}$$

we need an algorithm of identification of boundary value of diffraction parameter α_*. Analysis of dependencies $Q(\alpha)$ (fig. 2) shows that α_* value limiting Rayleigh scattering region is determined by wavelength λ.

Calculated dependencies (for soot) are given in fig. 3. These charts were built on the basis of condition of 5 % and 10 % deviation $Q(\alpha)$ of Rayleigh approximation from the exact Mie theory solution.

Thus, there are certain values $\alpha^* = f(\lambda)$ for each wavelength which make Rayleigh approximation valid for $\alpha < \alpha_*$ with specified controlled accuracy. These dependences are well approximated by the following function

$$\alpha_* = a \cdot \exp(-b\lambda) \tag{8}$$

where $[\lambda]$ = µm, and constants a and b depend on optical constants of material of studied particles.

The following expression for D_m can be obtained from (7) and (8):

$$D_m = \frac{\lambda_*}{\pi} a \cdot \exp(-b\lambda) \,.$$

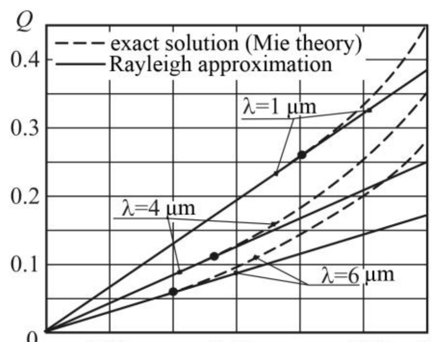

Fig. 2. Exact and approximated dependence of attenuation efficiency factor on diffraction parameter.

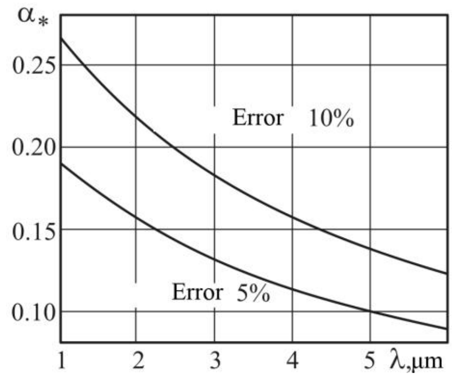

Fig. 3. $\alpha_* = f(\lambda)$ dependence for soot.

For λ = (1÷6) μm dependence of refractive index n and attenuation coefficient χ on wavelength λ is as follows n=1.6-0.3 λ, χ = 0.6 λ [2]; approximation error comprises (2.5÷3.0) %. Final expression for maximum particle size D_m for strictly determined dependence $\alpha_* = 0.217 \cdot \exp(-0.155\lambda)$ is as follows:

$$D_m = \frac{0.217\lambda_*}{\pi} \cdot \exp(-0.155\lambda) \quad (9)$$

Thus, the offered method makes it possible to determine both particle concentration and maximum particle size with controlled accuracy for aerosol media without any initial information about particle size distribution.

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