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RELATION BETWEEN THE ABSOLUTE ATTENUATION COEFFICIENT OF LASER-RADIATION INTENSITY IN AQUEOUS FOGS AND THE DROPLET CONCENTRATION

(Presented by Academician B. A. Vvedenskii, 26 II 1969)

The methods for studying the microstructure of fog by means of flow traps have found the widest application in the USSR and abroad (^{1}). Instruments of this type have serious shortcomings: 1) distortion of the droplet spectrum during aspiration of the sample and deposition on the obstacle; 2) the laboriousness and complexity of processing the measurement results. In the work of V. E. Zuev et al. (^{2}), devoted to the study of the spectral transparency of artificial fogs, a substantial discrepancy was found between the absolute attenuation coefficients measured with a photometer and those calculated from the results of processing samples from a flow trap. B. P. Koshcheev (^{3}), on the basis of extensive experimental material, showed that the cause of these discrepancies is the incorrect determination of the absolute droplet concentration by the flow trap.

In this connection, the possibility of using more advanced methods for reliable measurements of the microphysical characteristics requires special studies. For this purpose a series of experiments was carried out in which measurements of the optical transparency of fog with the aid of laser sources were accompanied by synchronous measurements of the parameters of its microstructure by a photoelectric method.

On the basis of this method, at the Institute of Radio Engineering and Electronics of the Academy of Sciences of the USSR a special electronic instrument, the "Aerosolometer," was developed, providing simultaneous measurements of seven droplet-size fractions in the range 0.5—14 μ by radius. The "Aerosolometer" is an integral analyzer operating in combination with photoelectric sensors developed at the branch of the Institute of Applied Geophysics (^{4}). Registration of droplet spectra in the instrument is carried out on paper tape by means of an electrically controlled digital printing device, the EUM-23. The "Aerosolometer" performs 6

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measurements of droplet spectra per minute* and can operate with any selected number of sensors from one to five (^{5}). The instrument has an automation unit that controls all processes in the operation of the equipment complex. Analysis of spectra is performed automatically in turn from each sensor. After sequential interrogation of all operating sensors, the analyzer is again connected to the first sensor. Thus, the "Aerosolometer" provides complete automation of microstructural measurements from the beginning to the end of an experiment.

Tests of the apparatus were carried out in the artificial-fog chamber of the IAG branch (^{6}), 18 m high and 15 m in diameter. The fog was produced by adiabatic expansion of air after a preliminary increase of the pressure in the chamber to 1.5 atm. The duration of a separate experiment, from the moment of fog formation to its complete dissipation, ranged from 40 to 90 min. As sources, optical quantum generators (OQG) of continuous radiation were used with wavelengths: $\lambda = 0.63;\ 1.15$

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* The duration of analysis of a sample from a sensor, including printing, is 10 sec.

and 3.39 μ. The length of the path of the laser beams in the chamber was 15 m. Measurements of the droplet spectra were made 6 times per minute by two photoelectric sensors*, located along the line of propagation of the laser beams at a distance of 1 m from one another. The reliability of the data from the measurements of concentration and droplet spectra was analyzed: 1) on the basis of a comparison of simultaneous readings from the two sensors, 2) by comparing the experimental attenuation coefficients of the laser radiation with theoretical ones calculated from the microstructural data.

The droplet concentration N in each experiment, in the range < 2000 particles/cm^3, gradually decreased as the fog dissipated to several tens of droplets per 1 cm^3 by the end of the experiment. The one-minute mean values of the concentrations

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and of the root-mean-square diameters of the droplets D_2, measured simultaneously by two sensors, practically coincided. The magnitude of the difference in N according to the data of the two instruments, on average over an experiment, did not exceed 30 particles/cm^3; the magnitude of the difference in D_2 was not more than 0.5 μ, which is within the accuracy of the measurements.

In the range $N > 2000$ particles/cm^3, the concentration curves in all experiments exhibited "saturation," indicating significant distortions of the concentration in this region due to the simultaneous entry into the working light volume of the photoelectric sensors of two or more droplets. The resolving power of the photoelectric instruments used, established experimentally, proved to be practically equal to the calculated value, which is 2200 particles/cm^3.

According to the microstructural data, the droplet spectra of the artificial fogs studied corresponded to the spectra of natural clouds and fogs of most types, while the limits of concentration variation were greater than in natural formations (7).

The range of one-minute mean values of D_2, measured at two points of the path, over the entire series of experiments was 6–13 μ, with the mean statistical value $\overline{D}_2 = 9.6 \pm 2.3$ μ. No regular changes in D_2 during an experiment were observed. There was good reproducibility of the fogs in terms of the mean droplet sizes from one experiment to another. The scatter of the values of D_2, averaged over the time of an experiment, throughout the entire series of experiments lay within 8–11 μ, with a root-mean-square deviation of ± 0.7 μ from $\overline{D}_2 = 9.6$ μ. This indicates that in the fogs investigated the mean droplet size along the path was practically constant in all measurements.

The results of comparing the one-minute mean values of the attenuation coefficients—experimental ones with calculated ones, computed from the microstructural data for a wavelength of 0.63 μ—are presented in Fig. 1**. For $N \leqslant 2200$ particles/cm^3, which corresponds to an optical thickness of the fog $\tau \leqslant 6$*, a satisfactory agreement between the calculated and experimental data was observed: averaged over all experiments, the value of the ratio $\alpha_{\text{calc}}/\alpha_{\text{exp}} = 1(\pm 19\%)$. At $N > 2200$ particles/cm^3, α_{calc} was smaller than α_{exp} owing to the underestimated value of the concentration measured beyond the resolving power of the photoelectric instruments.

The results of the investigations carried out make it possible to draw the following conclusion. The "Aerosolmeter," developed for studies of the microstructure of droplet-liquid clouds and fogs, when used together with photoelectric sensors within the range of their resolving power, provides reliable measurements not only of spectra but also of the absolute concentration of droplets. The relative

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* Three measurements per minute by each sensor, from the results of which the one-minute mean values of the microphysical characteristics were determined.

** The calculations were performed on a BESM-2 on the basis of the theory of single scattering, using exact formulas of the Mie theory and the gamma distribution of droplets by size.

Fig. 2. Relationship of attenuation coefficients α to droplet concentration N at $\lambda = 3.39\,\mu$ (1—$D_2 = 8.5 \pm 1\,\mu$; 2—$D_2 = 10.0 \pm 1\,\mu$)

Figure 2: Fig. 2. Relationship of attenuation coefficients α to droplet concentration N at $\lambda = 3.39\,\mu$ (1—$D_2 = 8.5 \pm 1\,\mu$; 2—$D_2 = 10.0 \pm 1\,\mu$)

complexity of the apparatus is compensated by the complete automation of the microstructural measurements. The apparatus can operate under both artificial and natural conditions.

Fig. 2. Relationship of attenuation coefficients α to droplet concentration N at $\lambda = 3.39\,\mu$ (1—$D_2 = 8.5 \pm 1\,\mu$; 2—$D_2 = 10.0 \pm 1\,\mu$)

In order to determine the correspondence between the laws of attenuation of coherent laser radiation in water fogs and single-scattering theory, and taking into account that the measured values of α are averages along the path of the laser beam, while the microstructure of the fog was determined only at two poorly spaced points of the path, at wavelengths 0.63, 1.15, and $3.39\,\mu$ the statistical relationship of α with the microphysical characteristics of the fog was analyzed. The principal factor determining the variations in the attenuation value in the fogs studied was the droplet concentration. The correlation coefficients between α and N at all wavelengths were 0.98—0.99. As an example, Fig. 2 presents, for the wavelength $3.39\,\mu$, the results of simultaneous measurements of one-minute mean values of α and N over the entire series of experiments in the coordinates N, α. The experimental data corresponding to different one-minute mean values of D_2 have different designations in the figure. No influence of the difference in the measured values of D_2 on the dependence $\alpha(N)$ was detected. This is explained by the fact that the path-averaged value of the droplet diameter $D_{2\text{av}}$ in the fogs studied practically did not change either during an individual experiment or from experiment to experiment. The scatter of the one-minute mean values of D_2 in individual measurements ($\sigma = \pm 2.5\,\mu$) was due to errors in measuring $D_{2\text{av}}$ caused by fluctuations. Therefore, the equations of the regression lines, determined by the least-squares method, at all wavelengths are expressed by straight lines of the form $\alpha(\lambda) = k(\lambda)N$. Coef-

* In this range the τ-component of the forward-scattered light is negligibly small (8).

coefficients $k(\lambda)$ for three wavelengths are as follows:

$\lambda,\ \mu$	0.63	1.15	3.39
$k(\lambda),\ \text{cm}^{-1}/\text{cm}^{-3}$	$1.70 \cdot 10^{-6}$	$1.73 \cdot 10^{-6}$	$2.04 \cdot 10^{-6}$

As a result of the comparison carried out at the wavelength $0.63\,\mu$, satisfactory agreement was found between the experimental correspondence coefficient and the theoretical one, calculated using the relation

$$a = k_{\text{theor}} N = {}^{1}/_{2}\pi D_2^2 \cdot 10^{-8} N \ (\text{cm}^{-1}), \qquad (1)$$

in which the value of this parameter averaged over all experiments was taken as D_2^2 ($k_{\text{theor}} = 1.55 \cdot 10^{-6}$ cm^2). The experimental value $k(0.63) = 1.70 \cdot 10^{-6}$ cm^2, according to (1), is equivalent to a root-mean-square droplet diameter $D_2 = 10.4\,\mu$, which differs only slightly (by no more than 8%) from the mean statistical value $\overline{D}_2$ determined from microstructural data ($\overline{D}_2 = 9.6\,\mu$).

According to the results of theoretical calculations for the fogs investigated, characterized on average by a gamma distribution of droplets by size with half-width parameter $\mu = 6$ and modal droplet radius $r = 3$–$4\,\mu$, the following relations should hold:

$$k(1.15)/k(0.63) = 1.02\text{–}1.03; \qquad k(3.39)/k(0.63) = 1.14\text{–}1.22.$$

Consequently, the experimental dependence of the correspondence coefficients on wavelength is in agreement with the theoretical one (see above).

Thus, the relationship between the attenuation characteristics of laser radiation and the concentration of droplets, with allowance for their sizes, at least in the range of fog optical thicknesses $\tau < 7$, corresponds to the theory of single scattering. This indicates that the laws governing the attenuation of coherent OKG radiation in water fogs in the spectral region 0.63–3.39 μ do not differ from the laws governing the attenuation of ordinary incoherent radiation from thermal sources.

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Note: Figure translations are in progress. See original paper for figures.