EFFECT OF RELATIVE HUMIDITY ON THE BACKSCATTERING COEFFICIENTS OF OPTICAL RADIATION IN SMOKES UNDER ELECTRIC FIELD

V.A. Donchenko, M.V. Kabanov, Yu.I. Kulakov, and V.P. Petrov

V.D. Kuznetsov Siberian Physicotechnical Institute at the State University, Tomsk
Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received March 18, 1992

The variations in backscattering coefficients of optical radiation by small particles of the wood smoke are experimentally studied as functions of relative humidity under the external electric field. It is shown that in the study of scattering of optical radiation in the atmosphere with an account of the variations in relative humidity it is necessary to take into account the effect of electric fields in the case in which electrocoagulation makes predominating contribution to the growth of aerosol particles.

The relative air humidity is one of the most important meteorological factors determining the variations in the structural, optical, and electric properties of atmospheric aerosol. It is well known that atmospheric aerosol is a complex conglomeration of different chemical compounds. In the course of interaction of small particles with water vapor in the atmosphere two processes are mainly observed[1]: the growth of particles with increase in the relative humidity η and the regular variations in the resulting refractive index: $n(\lambda) \to n_{H_2O}(\lambda)$ as $\eta \to 100\%$. The above–indicated processes result in opposite variations in the radiative aerosol characteristics, and first of all in backscattering. Depending on the process which gives the main contribution to the humidity variation, we can expect either decrease or increase of the backscattering coefficients.

It should be added that since atmospheric aerosol particles are charged and interact in the Earth's electric and humidity fields, in the study of scattering of optical radiation it is necessary to take into account the effect of electric characteristics. It was found that the transformation of the ionic mobility spectrum occured with increase of humidity in the atmosphere and led to the variation in the air electrical conductance. In this case the absorption of ions by aerosol particles increased and their intensive charging occured.[2,3] The presence of atmospheric electric field promoted the coagulation processes, adherence, and growth of particles and led to the transformation of the particle size spectrum, their shape, aggregate state, refractive index, orientation, and so forth.[4-6] Consequently, both electric and optical aerosol characteristics varied.

Thus, when solving the problems of atmospheric optics it is necessary to take into account both the humidity field gradient and electric field variations.

This paper presents the results of investigation of the variations in the backscattering coefficient by small particles of wood smoke (the Mie parameter $\rho = 4 \pm 3$) at the wavelength $\lambda = 1.06$ μm as functions of relative air humidity under the external electric field, since the smokes produced as a result of natural and artificial combustions are part of atmospheric aerosol and make a significant contribution to atmospheric pollution and formation of optical properties of the atmosphere. The smoke aerosol is formed by small particles with mean radius $r < 1$ μm.

Measurements were carried out in the chamber of artificial media with a volume of $3.5\times3.5\times10$ m^3. Relative humidity was measured by means of an aspiration psychrometer with a relative error of 1.5–2%. High humidity values in the range 70–90% were obtained by preliminary moistening of the chamber by the evaporation fog. The electric field was created by applying the controlled constant voltage at the 1×10 m^2 horizontal aluminum plates placed along the aerosol chamber. The distance between the plates was 1 m. The potential difference between the plates could vary from 0 to $5\cdot10^4$ V. A slightly modified optical scheme of this setup was described in Ref. 7. The chosen experimental conditions were characterized by the following parameters: optical axis of the receiver crossed the radiation beam axis at an angle of 3° at the distance $l = 4$ m from the front chamber wall, the beam diameter was $d = 0.5$ cm, the beam divergence was $\theta = 0.001$ rad, the diameter of the receiving objective was $D = 20$ cm, the angle of the field of view was $\psi = 0.01$ rad, the minimum distance to the scattering volume was $l_0 = 2$ m, the geometric thickness of the scattering layer was $L = 6.4$ m, and the base was $r = 22$ cm.

The radiation flux reflected from the medium for this configuration of the receiver and source in the single scattering approximation is given by the relation[8]:

$$F = K \frac{\alpha_s F_0}{\pi \Psi^2} f(\pi) \int_{l_0}^{L} \frac{l^{-2\alpha l}}{l^4} \Omega(l)\, G(l)\, \mathrm{d}l \,, \qquad (1)$$

where the solid angle $\Omega(l) = \pi\psi^2/4$ for $l \le D/\psi$, F_0 is the incident radiation flux, K is the efficiency of the optical train, $f(\pi)$ is the scattering phase function at an angle of 180°, α_s and α are the scattering and extinction coefficients in the medium and without absorption $\alpha_s = \alpha$, and $G(l)$ is the common area of intersection of the cones of radiation and the field of view in the plane perpendicular to the receiving axis and a for $l_0 \le l \le L$ and narrow radiated beam $G(l) = \pi\psi^2 l^2$.

By substituting the initial parameters into Eq. (1) and integrating we obtain the initial relation

$$F = K \frac{F_0 \pi \Psi^2}{8} \frac{\beta_\pi}{\alpha} \left[e^{-2\alpha l_0} - e^{-2\alpha L} \right] , \qquad (2)$$

where β_π is the backscattering coefficient.

0235-6880/92/07 427-04 $02.00

As can be seen from this relation, we can determine the backscattering coefficient β_π by measuring the extinction coefficient in the medium and the reflected radiation flux scaled to the incident radiation flux of the source in the experiment.

The variation in the reflected radiation signals normalized to the source signals as a function of the extinction in the scattering medium for different electric field intensities and relative humidity η in the range from 30 to 90% is shown in Fig. 1.

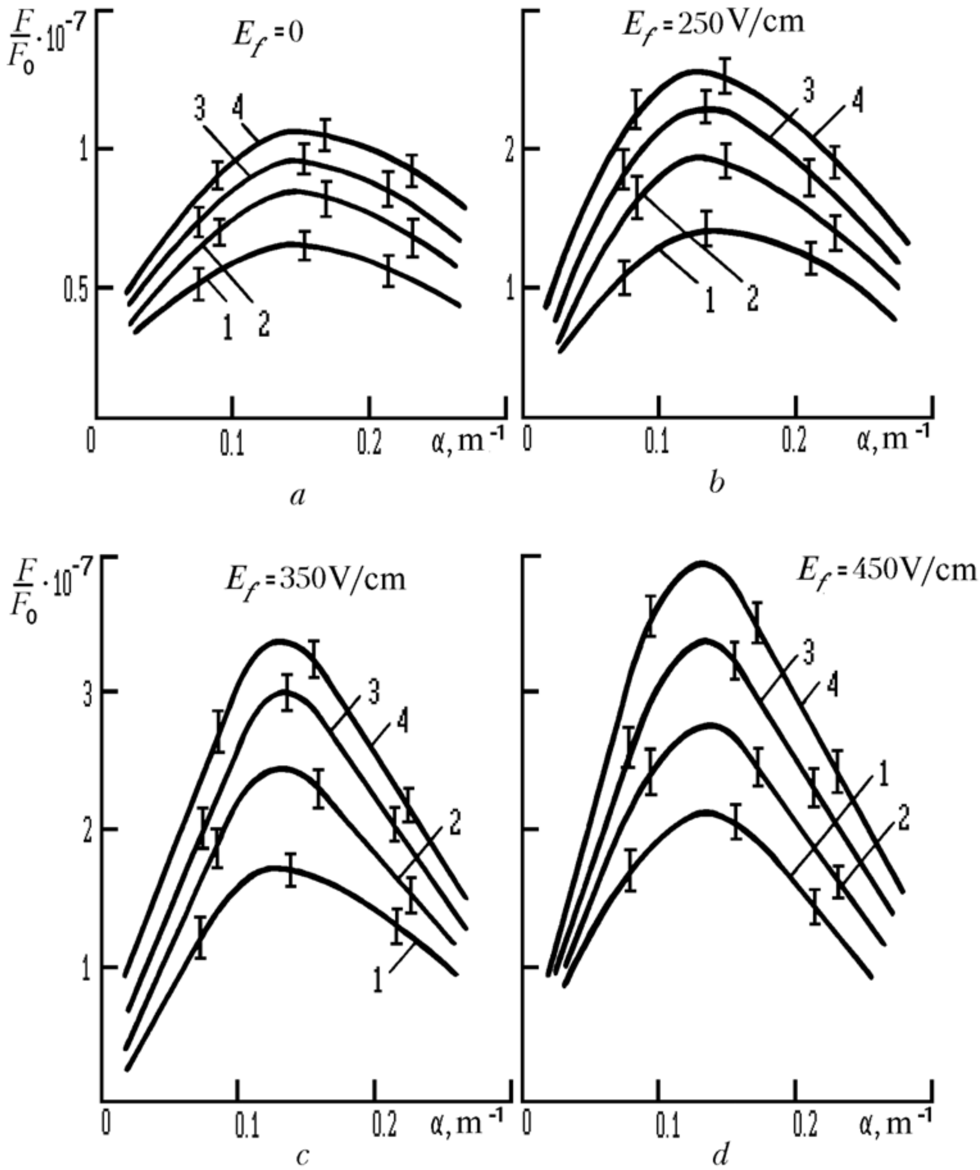

FIG. 1. Variation in the normalized backscattered radiation flux as a function of the extinction coefficient α *for different* E_f *and relative humidity* η*: 1)* 30%, *2)* 56%, *3)* 76%, *and 4)* 90%.

The curves are derived from a five–realization average. A confidence level (vertical bars) shows the standard deviation. The rms measurement error is less than 2%.

The characteristic behavior of the curves in Fig. 1 is determined by the dynamics of sedimentation of smoke aerosol and is exactly described by Eq. (2) in the single scattering approximation. At the start of the process the backscattered signal is caused by the radiation extinction along the path to the scattering volume. As the smoke sediments the reflected signal increases, reaches a maximum at $\alpha = 0.13\ m^{-1}$, and then decreases due to the decrease of the number density of aerosol particles in the volume.

Without external electric field (Fig. 1) the increase in the backscattered signal is observed as the relative air humidity increases from 30 to 90%. It is explained by the fact that the coagulation intensifies with increase in the relative humidity due to the capillary coalescence forces, which leads to the growth of the smoke particles. In addition, the smoke aerosol is charged in the process of formation, and the increase in the humidity of the air medium is accompanied by different electric phenomena in the medium and on the surface of aerosol particles (the oriented absorption of water molecules on the particle surfaces, charging and recharging of particles, polarization of charges on the particles, etc.). Due to these processes the induced charges arise on the moistened particles, which results in their dipole charging and increases the probability of their coalescence. This effect is especially significant for the particles with the size of several tenth and hundredth of microne.[4] The external field, which simultaneously ionizes the medium in the chamber due to corona discharges at the edges of the capacitor plates results in intensive recharging of aerosol particles by deposition of aeroions on their surface and in additional drift of charged particles under the electrostatic forces of the field. These processes intensify the coagulation, which leads to the intensive growth of particles[6] and to the increase in the reflected signal (Fig. 1*b*, *c*, and *d*). The maximum of the backscattered signal sharply increases with increase in the relative humidity and electric field intensity.

The variation in the conductance of the medium in logarithmic scale as a function of electric field intensity and relative humidity in a clean chamber is shown in Fig. 2. The conductance of the medium was measured by the conduction current in the capacitor

$$\sigma = I/(SE_f) ,$$

where I is the current in the capacitor, S is the area of the plate, and E_f is the field intensity.

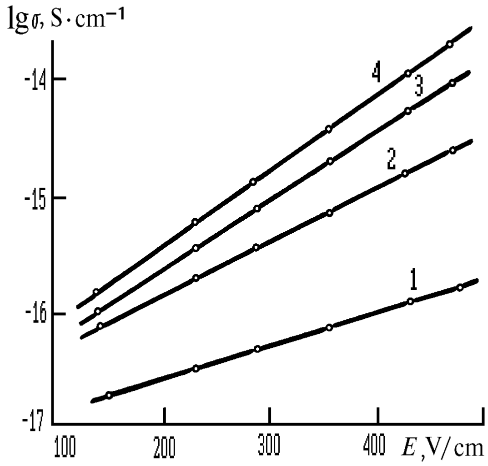

FIG. 2. Variation in the electroconductance of the medium as a function of the electric field intensity for the humidity η *in the clean chamber: 1)* 30%, *2)* 56%, *3)* 76%, *and 4)* 90%.

As can be seen from Fig. 2, the conductance of the air medium in the chamber increases with increase in the electric field and relative humidity by two orders of magnitude. So, the conductance increases from $1.8{\cdot}10^{-17}...1.6{\cdot}10^{-16}$ up to $1.2{\cdot}10^{-16}...1.2{\cdot}10^{-14}$ S·cm^{-1} as the electric field intensity increases from 150 to 450 V/cm and the relative humidity increases from 30 to 90%, respectively. This shows that the number of aeroions increases with the electric field intensity, while the increase in the relative air humidity in the chamber intensifies the absorption of aeroions by water vapor, which results in increasing the conductance. The same process is observed in the case of the presence of smoke aerosol in the chamber. The conductance of smoke aerosol as a function of humidity for different electric field intensities is shown in Fig. 3. It can be seen that both factors (field intensity and humidity) promote intensive charging of aerosol particles, which results in the increase in the conductance of the aerosol medium. The increase of the electrostatic charge on aerosol particles interacting under the external electric field always promotes the increase of the coagulation rate,[3,4] which results in the growth of the smoke aerosol conglomerates.

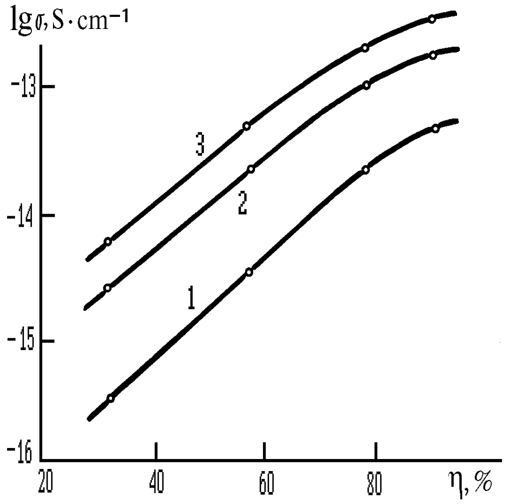

FIG. 3. Variation of the electroconductance of the smoke aerosol as a function of humidity for different values of the electric field intensity E_f*: 1)* 260 V/cm, *2)* 360 V/cm, *and 3)* 450 V/cm.

The dependence of backscattering coefficients of optical radiation on the relative humidity for different electric field intensity is shown in Fig. 4. The backscattering coefficients were calculated for the medium with the extinction coefficient $\alpha = 0.13$ m^{-1}. It can be seen from Fig. 4 that the backscattering coefficient starts to increase slowly with relative humidity from $\eta > 60\%$ without the external electric field. After switching on the external electric field the backscattering coefficient increases with humidity with a higher rate by a factor of 2–4 (in the range E_f = 250–450 V/cm). Such variations in the backscattering coefficient of optical radiation is caused, proceeding from the above–given reasons, only by coagulation processes which occur in the smoke aerosol.

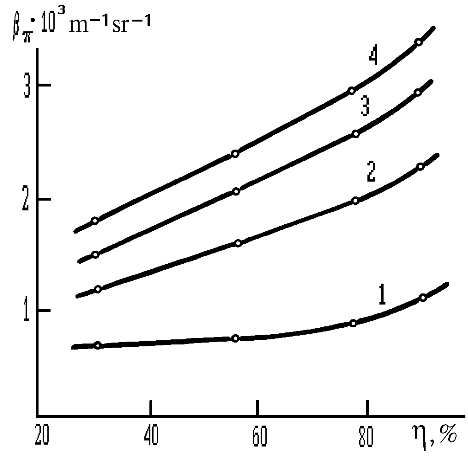

FIG. 4. Backscattering coefficient as a function of humidity for different values of the electric field intensity E_f *: 1)* 0, *2)* 250, *3)* 350, *and 4)* 450 V/cm.

The effect of relative air humidity on the lidar ratio in the aerosol medium produced by the exhaust of diesel fuel and in sounding of the natural atmospheric aerosol as well as on the shape of the angular characteristics of light scattering by the wood smoke was studied in Refs. 9–11. It was shown that the dependence of the refractive index of aerosol particles on the variations in the relative humidity leading to the contrary results made the most important contribution to the variations in the optical characteristics. It is explained by the characteristics of the examined aerosol and its formation.

Thus it is shown that in the study of optical radiation scattering in the atmosphere it is necessary to take into account the effect of the electric fields in the case in which electrocoagulation makes predominating contribution to the growth of aerosol particles. Especially this is manifested in thunderstorms.

REFERENCES

1. G.V. Rozenberg, G.I. Gorchakov, et al., in: *Atmospheric Physics and Climate Problems* (Nauka, Moscow, 1980), pp. 216–257.
2. V.V. Smirnov, Tr. Exp. Met. Akad Nauk SSSR, Obninsk (1983), No. 30 (104), pp. 64–106.
3. H.L. Green and W.R. Lane, *Particulate Clouds: Dusts, Smokes, and Mists 2 nd ed.* (Spon., London, 1964); (Van Nostrand, Princenton, N.Y., 1964).
4. L.S. Ivlev, *Chemical Composition and Structure of Atmospheric Aerosols* (State University Publishing House, Leningrad, 1982).
5. V.I. Smirnov, in: Tr. Centr. Aerolog. Observ., (1969) No. 92, pp. 82–106.
6. E.V. Genin, V.A. Donchenko, M.V. Kabanov, et al., Izv. Vyssh. Uchebn. Zaved., Ser. Fiz., No. 2, 82–87 (1986).
7. V.A. Donchenko, Yu.I. Kulakov, and V.V. Terent'ev, in: *Investigations in Electrodynamics and Electromagnetic Wave Propagation* (State University Publishing House, Tomsk, 1977), pp. 180–184.
8. V.E. Zuev and M.V. Kabanov, *Transfer of Optical Signals in the Earth's Atmosphere* (Sov. Radio, Moscow, 1977).
9. B.V. Kaul' and O.A. Krasnov, in: *Problems of Remote Sensing of the Atmosphere*, Tomsk Affiliate of the Siberian Branch of the Academy of Sciences of the USSR, Tomsk (1976), pp. 98–104.
10. Yu.S. Balin, G.M. Krekov, I.V. Samokhvalov, and R.F. Rakhimov, Meteor. Gidrol., No. 8, 114–119 (1978).
11. V.S. Kozlov and V.Ya Fadeev, in: *Abstracts of Reports at the Fifth All–Union Symposium on Laser and Acoustic Sounding of the Atmosphere*, Tomsk (1978), pp. 139–142.