EFFICIENCY OF THE PULSED CO_2 LASER RADIATION TRANSFER THROUGH THE DROPLET AND CRYSTAL MEDIA

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We present here some results of our investigation into the propagation of a high-power focused laser beam through an ice fog along a near ground path in the atmosphere. Investigated has been the influence of aerosol microstructure on the integral transmission of the medium within the beam channel. Interpretation of the experimental data is also discussed in this paper.

Investigations into the propagation of a pulsed CO_2-laser radiation carried out on atmospheric paths allowed us to reveal the main factors that govern the attenuation of radiation in the atmosphere. It was established, from these studies, that the beam attenuation depends on the beam parameters and on the physical situation along the propagation path and its evolution[1–7] as well. The data of field experiments that have already been interpreted mostly refer to warm seasons, that means that in these experiments the situations occurred when there were such aerosol formations in the atmosphere as fog, drizzle, and rain.

In this paper we present a study of the influence of the aerosol phase state and microstructure on the optical properties of the atmosphere within the channel of beam propagation. The ice fog observed in the atmosphere is taken as an example of a crystal medium.

That type of aerosol formation normally occurs in the atmosphere at temperatures below 258 K and relative humidity of air exceeding 80% (see Ref. 8). It is known that ice crystals formed in the near ground atmospheric layer most frequently are ice plates and prisms with the size from 2 to 300 μm. The ice crystals are normally formed around one or several crystallization nuclei which are solid particles of 0.1 to 3 μm size. They also include many much smaller nuclei about 0.01 μm size. According to Ref. 9 the concentration of ice crystals in the atmosphere can reach 200 to 300 particles per cubic meter.

Some laboratory experiments on studying the propagation of CO_2-laser radiation in model water droplet and crystal clouds have been carried out in the study discussed in Ref. 10. This experiments showed certain deterioration of the conditions for propagation of radiation. It was also shown in Ref. 10 that the onset of the medium turbidity occurs in both cases of water droplet and ice crystal fogs similarly. Measurements of the mean radius of secondary aerosol particles formed due to the destruction of crystal by laser radiation did not allow us to reveal any dependence on the initial microstructure ($a_{\rm eff} \sim 4 \div 15$ μm) and the medium temperature (up to 240 K). Here $a_{\rm eff}$ is the radius of a sphere equivalent in volume. Energy density of the incident radiation pulse, w, varied in these experiments from 1 to 253/cm^2.

It is hardly possible to adequately understand the physical aspects of a pulsed CO_2-laser radiation propagation in winter atmosphere without relevant laboratory studies of the radiation interaction with an elementary volume of a medium and/or with individual aerosol particles. Unfortunately, no experimental and theoretical data on the interaction of radiation with aerosol particles characteristic of ice fogs (plates and prisms) are now available in literature.

In this paper we analyze the data of field experiments on studying the attenuation of pulsed CO_2-laser radiation by crystal fogs along a near ground atmospheric path. The description of the experimental technique used in this study can be found in Ref. 1. The geometry of the laser beam ($F_1/R_0 \sim 9 \cdot 10^2$) has been the same in all measurement session of this complex experiment. Here F_1 is the focal length of the transmitting telescope and R_0 is the initial radius of the laser beam used. The beam energy provided achieving the thresholds of the aerosol droplet explosion and optical breakdown of the medium.

The molecular and aerosol components of the medium extinction coefficient were $\alpha_M \sim 0.033$ to 0.045 km^{-1} and $\alpha_{\rm aer} \sim 0.014$ to 0.281 km^{-1}, respectively. Here $\alpha_M = \alpha_{H_2O} + \alpha_{CO_2}$, α_{H_2O} is the absorption coefficient of water vapor at $\lambda = 10.6$ μm and α_{CO_2} is the resonance absorption coefficient of CO_2 molecules.

As is seen from Fig. 1, the initial optical thickness of the atmospheric path in different meteorological situations significantly changes under the action of laser radiation. Various types of the optical weather in the atmosphere, like fogs, mists, drizzle, and rain, have been thoroughly analyzed in Refs. 5 and 6 together with their influence on the extinction coefficient of the atmosphere along measurement paths. The experimental data obtained

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in ice fogs well agree with the behavior of $K(\tau_0)$ measured in water droplet media. Here $K(\tau_0) = \Delta\tau / \tau_0$, $\Delta\tau = \tau_0 - \tau_k$, τ_k is the optical thickness of the medium after the termination of the laser pulse. The range of $\Delta\tau / \tau_0$ variations in rain and ice fogs is much wider due to the contribution from the background atmospheric aerosol. The values $\Delta\tau/\tau_0$ below −10 can be observed in this case depending on the beam energy density.

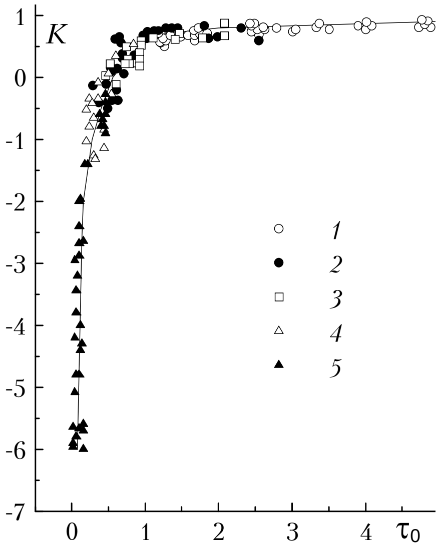

FIG. 1. Change of optical thickness of the measurement path due to the action of single pulse of CO_2 *laser radiation under different meteorological conditions like fog (1), mist (2), drizzle (3), rain (4), and ice fog (5).*

As is seen from Fig. 1, the value $\Delta\tau/\tau_0$ never reached positive values in ice fog, that means a significant deterioration of the atmospheric transmission under the action of laser radiation. It is characteristic of the water droplet media, at τ_0 values observed, that the transmission of the atmospheric channel gradually increased. This fact can be explained by a gradual washing out of the coarse fraction of the background aerosol, whose particles cause the initiation of the optical breakdown along the path what, in its turn, results in an enhanced radiation extinction. An increase in the energy of radiation propagated both in water droplet and crystal media leads to appearance of the breakdown cells around smaller particles thus increasing the concentration of plasma cells (see Fig. 2). To provide better illustration of this conclusion, we present in this figure only the data obtained under stable atmospheric conditions (no wind was observed during several hours). The interval between successive irradiations of the medium with laser pulses did not exceed 4 min.

Independent instrumental control of the aerosol along the atmospheric path showed the concentration of the coarse aerosol particles ($a > 1$ μm) to be equal or below 10^{-2} cm^{-3}.

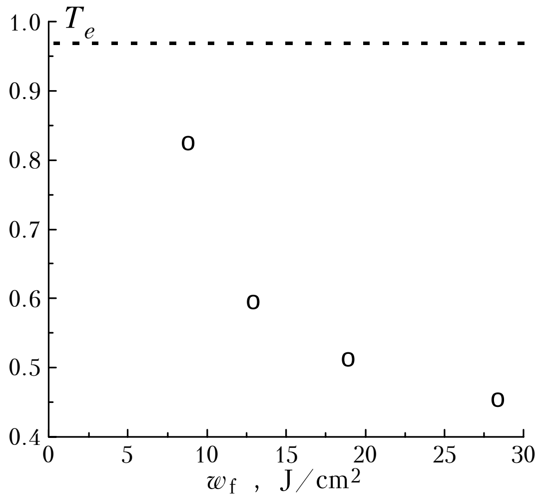

FIG. 2. The dependence of the transmission coefficient measured along an atmospheric path on the radiation energy density in the focal plane of the transmitting telescope in ice fog, $a_M = 0.041$ km^{-1}; $a_{aer} = 0.014$ km^{-1}. *Dashed straight line presents the calculated transmission coefficient in a linear mode (*$T_e = 0.97$*). No wind was observed during these measurements.*

Let us define the integral transmission of the aerosol medium, whose extinction coefficient α is a nonlinear function of the laser beam intensity, as the ratio[6]

$$T_e(z;\,t) = \frac{E(z;\,t)}{E(0;\,t)} = \frac{\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty} \mathrm{d}^2\mathbf{R} \int\limits_0^t I(\mathbf{R}';\,z;\,t')\,\mathrm{d}t'}{\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty} \mathrm{d}^2\mathbf{R} \int\limits_0^t I(\mathbf{R}';\,0;\,t')\,\mathrm{d}t'}\,, \quad (1)$$

where R and z are the longitudinal and the transverse coordinates in the beam, t is time. In the case when no refraction occurs and neglecting wind drift of the medium, the beam intensity is described by the following transfer equation

$$\frac{\partial I(\mathbf{R},\,z;\,t)}{\partial z} + \Theta(\mathbf{R},\,z)\,\nabla_R\,I(\mathbf{R},\,z;\,t) + $$
$$+ I(\mathbf{R},\,z;\,t)\,\nabla_R\,\Theta(\mathbf{R},\,z) = -\alpha(\mathbf{R},\,z;\,t)\,I(\mathbf{R},\,z;\,t), \quad (2)$$

in combination with the equation for the “diffraction” ray

$$\frac{\mathrm{d}\,\mathbf{R}_\mathrm{d}}{\mathrm{d}z} = \Theta(\,\mathbf{R},\,z); \quad \frac{\partial\Theta(\mathbf{R},\,z')}{\partial z'} = \frac{1}{2}\,\nabla_R\,\frac{\Delta_R\,A(\mathbf{R},\,z')}{k^2A(\mathbf{R},\,z')}\,,$$

the boundary conditions being

$$I(z' = 0) = I_0\,;\ R_\mathrm{d}\,(z' = z) = R;$$

$$\frac{\mathrm{d}\,\mathbf{R}_\mathrm{d}\,(z' = 0)}{\mathrm{d}z'} = \Theta_0.$$

Here $\mathbf{\Theta} = \nabla_R \phi / k$ is the transverse component of the vector of the beam energy transfer, ϕ is the real phase, A is the real amplitude of the wave, and k is the wave number. Note that we consider here a coherent radiation.

In the case of a Gaussian beam profile, the equation (2) is reduced, in a linear approximation, to the following integral relationship[6]

$$I(\mathbf{R}, z, t) = I_0(t) \exp\{-R^2/R_0^2\, g^2(z) -$$

$$- \tau_N(\mathbf{R}, z, t)\}/g^2(z), \qquad (3)$$

where $\tau_N(\mathbf{R}, z, t) = \int\limits_0^z \alpha(\mathbf{R}_d(z'), z', t)\mathrm{d}z'$ is the "nonlinear" optical thickness calculated along the "diffraction" ray; $g(z) = [(1 - z/F)^2 + z^2/(k^2R_0^4)]^{1/2}$ is the dimensionless width of the Gaussian beam, F is the curvature radius of the phase front at $z = 0$.

As follows from Eqs. (1) and (3), in order to calculate the integral transmission of the aerosol medium at the point ($\mathbf{R}$, z) at an arbitrary moment in time, one needs information about the aerosol extinction coefficient α and its dependence on the beam energy parameters. The latter dependence can either be constructed theoretically based on models of particle destruction by laser radiation or established experimentally. In the below discussion, we shall use the models of the aerosol extinction coefficient developed in Ref. 11.

The destruction of particles due to explosion under the action of a high-power pulsed CO_2-laser radiation is the main nonlinear effect governing the formation of the water droplet aerosol extinction[12] at the laser beam intensity below the breakdown threshold. The explosion of a droplet occurs at the temperature inside a droplet close to spinodal temperature, which is about 593 K (see Ref. 13) at a standard pressure. Such an overheating inside a droplet causes an intense generation and growth of the vapor bubbles, which, in their turn, cause the destruction of the particle or its surface layer resulting in the water vapor release and appearance of smaller particles.

The explosion can be either a single or multistage process depending on the particle size and the radiation energy. In both case there occurs an explosion boiling up of water followed by the vapor release from the zone of the initially metastable overheating. In the case of small particles ($2\alpha_{\mathrm{ab}}\, a < 1$, where α_{ab} is the volume absorption coefficient of the droplet substance) and quasihomogeneous distribution of the absorbed energy over the particle volume, the explosion results in a complete destruction of the particle. On the other hand a layer-by-layer explosion regime[14] takes place at an intense heating (~10^8 K/s) of large particles ($2\alpha_{\mathrm{ab}}\, a > 1$). In the later case the explosion boiling up takes place in the zones of energy release at the illuminated and shadowed portions of the particle's surface. The entire process of the droplet explosion destruction can be presented as a succession of heating, boiling up, and flying off of the superheated near surface layer having the thickness on the order of the absorption length, $\alpha_{\mathrm{ab}}^{-1}$. Such an understanding of this process allows the consideration of the explosion process within a layer to be done within the model of a homogeneous phase explosion developed in Ref. 12.

Let us follow the scheme, when treating the interaction of radiation with ice crystals, according to which first occurs the crystal melting followed by instantaneous formation of a droplet with the equivalent volume. Then this liquid droplet undergoes heating and boils up.[15] As estimations showed the energy consumption at the first stage is much lower than at the second one. For this reason one may use the aerosol extinction coefficient models developed for water droplet aerosol formations.[11]

Let the extinction coefficient of the coarse aerosol fraction in an intense field of laser radiation be presented as α a $\alpha_{\mathrm{a}} + \alpha_{\mathrm{b}}$, where

$$\alpha_{\mathrm{a}} \equiv \alpha_0 \text{ a } \pi N_0 \int\limits_0^\infty f_0(a)\, a^2 K_{\mathrm{ex}}(a)\, \mathrm{d}a, \quad w < w_{\mathrm{ex}}\,; \quad (4)$$

$$\alpha_{\mathrm{a}} \text{ a } \alpha_n^j + \alpha_{\mathrm{d}}^j,\ j\, w_{\mathrm{ex}} \le w \le (j{+}1)\, w_{\mathrm{ex}},\ j \text{ a } 1, 2, \dots, J.$$

The values of α_n^j and α_{d}^j are calculated as follows:

$$\alpha_n^j \text{ a } \pi N_0 \int f_0(a)\, a_j^2\, K_{\mathrm{ex}}(a_j)\, \mathrm{d}a_j$$

is the extinction coefficient of the droplets kernel parts remained after peeling j layers off due to explosion;

$$\alpha_{\mathrm{d}}^j \text{ a } \alpha_{\mathrm{ab}} N_0 \sum_{i=1}^{j} (1 - X_{\mathrm{ex}}^i) \exp\{-\beta_i(w)(w - i\, w_{\mathrm{ex}})\} \times$$

$$\times \int f_0(a)\, V_{\mathrm{a}}^i[a_i(a_0)]\mathrm{d}a$$

is the coefficient of extinction by the fragments formed due to the destruction of j layers.

Here N_0 and $f_0(a)$ are the initial concentration and size distribution function of the equivalent droplets; a_i a $[a_{i-1}^3 - (3a_{i-1}^2/2\alpha_{\mathrm{ab}})]^{1/3}$ is the size of a kernel after peeling i layers off, V_a^i a $2\pi\, a_{i-1}^2/\alpha_{\mathrm{ab}}$ is the volume of the ith surface layer; X_{ex}^i, $\beta_i(w)$, and w_{ex} are the basic parameters of the phase explosion process, namely, the fractional rate of the explosion vaporization of a droplet (~0.1 to 0.4 for water under standard pressure), the efficiency of the fragments vaporization (~0.07 to 0.21 cm^2/J), and the threshold energy density of radiation[12] that causes the droplet explosion (~1.5 to 2.0 J/cm^2).

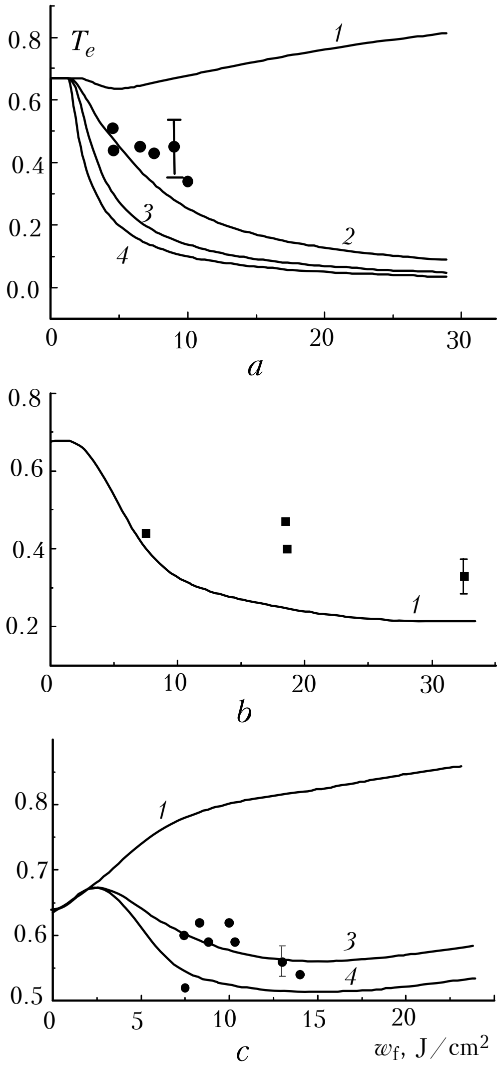

FIG. 3. The dependence of the path transmission coefficient on the energy density of radiation for ice fog (a) with $\tau_0 = 0.4$, *rain (b) with* $\tau_0 = 0.4$, *and fog (c) with* $t_0 = 0.45$. *Figures at the curves show different values of* N_g: $N_g = 0$ *(1),* 0.001 *(2),* 0.01 *(3), and* 0.1 cm^{-3} *(4).*

The extinction of radiation by the optical breakdown plasma cells (the coefficient α_b) formed around the particles of the background aerosol has been taken into account according to the model of equalized parameters.[16] It is assumed, within this model, that the breakdown cells appear immediately at the moment when the beam intensity $I(\mathbf{R}, z)$ reaches certain threshold value I_{bd} and their subsequent growth obeys the light detonation mechanism. Then at the intensity decreased below the threshold, $I < I_{bd}$, the breakdown cells also immediately disappear. The breakdown threshold intensity of radiation at $\lambda = 10.6$ μm was taken to be $I_{bd} = 10^8$ W/cm^2 (see Ref. 17). By substituting expressions (3) and (4) into the equation (1), we obtain a solution of the problem stated.

Figure 3 presents several $T_e(w_f)$ dependences obtained by numerically solving Eq. (1) for different meteorological situations along the path. In our calculations, we also varied the concentration of the coarse fraction of the background aerosol N_g whose particles cause the initiation of the optical breakdown. The particle size distribution of the aerosol ensemble was assumed to be the Γ distribution with the parameters $a_m = 5$ μm, $\mu = 3$ (ice fog); $a_m = 5$ μm, $\mu = 3$ (fog), and $a_m = 500$ μm, $\mu = 3$ (rain). The data for modeling were borrowed from experiments. In the case of an ice fog, we took $a_m = a_{eff}$. As is seen from the data presented, the main mechanism of the transmission decrease in water droplet and ice fogs is the optical breakdown on the particles of background aerosol, while in the rain this same phenomenon occurs due to the explosion fragmentation of droplets.

To summarize, we could suggest the following conclusions drawn from the above discussion:

1. Physical interpretation of field experiments essentially depends on the model of the aerosol extinction coefficient used.

2. The ice crystals in an ice fog combine the crystallization nuclei into large aerosol particles thus hindering their gravitational sedimentation from the ground atmospheric layer. At a fixed radiation energy, this results in a practically constant concentration of the plasma cells on solid aerosol particles. As a result, we have an enhanced extinction of high-power radiation in ice fogs as compared to that in water droplet formations.

REFERENCES

1. Yu.V. Akhtyrchenko, E.B. Belyaev, Yu.P. Vysotskii et al., Izv. Vyssh. Uchebn. Zaved., Fizika, No. 2, 5–13 (1983).

2. N.A. Blinov , I.A. Leont'ev , E.G. Ryzhkov et al., Kvant. Elektron. **12**, No. 10, 2147–2149 (1985).

3. Yu.V. Akhtyrchenko, Yu.P. Vysotskii, S.L. Golub et al., Trudy Inst. Eksp. Meteorol., No. 40(123), 99–103 (1986).

4. Yu.D. Kopytin, V.I. Kokhanov, V.A. Pogodaev, and S.A. Shishigin, Kvant. Elektron. **15,** No. 2, 405–411 (1988).

5. A.A. Zemlyanov, G.A. Mal'tseva, and V.A. Pogodaev, Atm. Opt. **2**, No. 6, 499–504 (1989).

6. Yu.E. Geints, A.A. Zemlyanov, and V.A. Pogodaev, Atm. Opt. **2**, No. 9, 798–803 (1989).

7. V.A. Pogodaev, Atmos. Oceanic Opt. **6**, No. 4, 211–213 (1993).

8. V.N. Uzhegov, Yu.A. Pkhalagov, and N.N. Shchelkanov Atmos. Oceanic Opt. **7**, No. 8, 570–574 (1994).

9. *Atmosphere. Handbook* (Gidrometeoizdat, Leningrad, 1991), 509 pp.

10. V.A. Bel'ts, O.A. Volkovitskii, A.F. Dobrovolskii et al., Kvant. Elektron. **12**. No 5, 1027-1033 (1985).

11. Yu.E. Geints, *"Interaction of Power Laser Radiation with Absorbing Water Aerosol and Optical*

Consequences," Cand. Phys.-Math. Sci. Dissertation (Tomsk, 1990), 167 pp.

12. Yu.E. Geints, A.A. Zemlyanov, and V.A. Pogodaev, and E.A. Rozhdestvenskii, Atm. Opt. **1**, No. 3, 27–34 (1988).

13. V.P. Skripov, E.N. Sinitsin, P.A. Pavlov et al., *Heat Physical Properties of Liquids in Metastable State. Handbook* (Atomizdat, Moscow, 1980), 208 pp.

14. Yu.E. Geints, A.A. Zemlyanov, and V.A. Pogodaev, Atmos. Oceanic Opt. **6**, No. 11, 815–820 (1993).

15. M.P. Gordin, A.V. Sokolov, and G.M. Strelkov, *Itogi Nauki i Tehniki, Radiotehnika* (VINITI, Moscow, 1980) Vol.20, pp. 20–289.

16. Yu.V. Akhtyrchenko, L.A. Vasil'ev, and Yu.P. Vysotskii, in: *Abstracts of Reports at II All-Union Meeting on Laser Radiation Propagation in Disperse Medium,* Obninsk (1981), pp. 3–8.

17. V.E. Zuev, A.A. Zemlyanov, and Yu.D. Kopytin, *Nonlinear Atmospheric Optics* (Gidrometeoizdat, Leningrad, 1989), 256 pp.