FAST ESTIMATION OF HIGH-POWER PULSE CO_2-LASER RADIATION ATTENUATION ALONG GROUND ATMOSPHERIC PATHS

N.N. Bochkarev, Yu.E. Geints, A.A. Zemlyanov, A.M. Kabanov, and V.A. Pogodaev

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received March 20, 1998

The model for fast estimation of high-power pulse CO_2-laser radiation attenuation along ground paths under conditions of haze, fog, drizzle, and rain is proposed. The model is based on the idea that physical processes of radiation interaction with aerosol under laboratory conditions are adequate to that under field conditions. This idea was verified by remote acoustic measurements.

INTRODUCTION

The interest in the problem of high-power laser radiation (HPLR) propagation in the atmosphere is conditioned by practical needs in long-distance transport of light energy. The above problem becomes more urgent with the advent of mobile and independent HPLR sources of various implementation.[1]

The first results on the experimental investigation of HPLR beams propagation along ground paths have shown that the radiation extinction by the medium depends nonlinearly on the laser radiation power at the transmitting aperture.[2,3] The process of radiation interaction with the medium on the propagation path depends greatly on the type and microphysical composition of a specific meteorological formation, as well as the power parameters of a beam, beam structure, time operating conditions, focusing conditions.[2,4–10]

This paper describes a model for *a priori* estimate of energy attenuation of HPLR from pulse CO_2 lasers of microsecond duration under conditions of haze, fog, drizzle, rain on the ground atmospheric paths.

Construction of the model requires a detailed knowledge of the coefficient of HPLR extinction by the atmosphere in dependence on the energy parameters of radiation. As a rule, studies of such dependence are made under controlled laboratory conditions individually for gaseous and aerosol components of the atmosphere. A necessary condition for development of the model is the assurance that the physical processes on the HPLR interaction with atmospheric components under laboratory and field conditions are identical.

1. THE COEFFICIENT OF HPLR EXTINCTION BY THE NEAR-GROUND ATMOSPHERE

In the window of relative atmospheric transmittance (8–13 μm), radiation of 10.6 μm wavelength and with the energy insufficient for development of nonlinear effects is attenuated due to the continuous absorption by water vapor, selective absorption by a number of gas components of the atmosphere (H_2O, CO_2, O_3, NH_3, SO_2), aerosol absorption, and scattering (see Refs. 11 and 12, and references therein). Each of these factors depends on the atmospheric conditions, namely, temperature, pressure, concentration of absorbing gases, chemical composition and microstructure of aerosols. It has been found that the selective absorption of minor gas components at a wavelength, being of interest for us, can be neglected.[13] The analysis of the published results of investigations into the mechanism of radiation absorption by water vapor enabled the authors of Ref. 14 to propose the engineering technique for estimating the water vapor continuous absorption coefficient α_{H_2O} (with 2–3% error) describing the empirical data known from the literature. The estimate of the resonance absorption coefficient α_{CO_2} is also given in Ref. 14.

A distinguishing feature of the real atmosphere from the controlled model gas media is the availability of the aerosol component. At $\lambda = 10.6$ μm, the spectral transmission of radiation is determined simultaneously by the two most variable components of the atmosphere: water vapor and aerosol. An separate estimation of influence of these factors on the final result is difficult, on the one hand, because of the overlapping their contributions into the radiation extinction and, on the other hand, due to relation between the aerosol extinction coefficient α_a and the characteristics of atmospheric humidity. The detailed investigations into the role of aerosol in extinction of optical radiation in the linear mode of propagation have been systematized in Refs. 12 and 15. The recommendations have been developed on the quantitative account for aerosol extinction under various optico-meteorological situations.

The nonlinear components of the coefficient of radiation extinction by the atmosphere can manifest themselves only when the energy conditions in a laser beam exceed a certain threshold value. The volume radiation absorption coefficient at $\lambda = 10.6$ μm of the atmospheric gas component $\alpha_M = \alpha_{H_2O} + \alpha_{CO_2}$ depends on the time and power parameters of radiation propagating in the atmosphere. The conditions can be

0235-6880/98/07 602-07 $02.00

obtained under which some decrease of the above coefficient is observed.

The reason for such dependence is the two effects[13]: the spectroscopic saturation effect on the *P*-branch transitions of the 00^01-10^00 band of atmospheric CO_2, characterizing by the threshold intensity $I_{sat} \sim (0.2–0.5)10^6$ W/cm^2; the brightening effect of the far wing of the 010 H_2O band with the threshold intensity $I_w \sim (2–3)10^6$ W/cm^2. The estimates of contribution of the above effects to the dependence of the HPLR nonlinear extinction coefficient $\alpha(E_0)$ for the considered optico-meteorological situations indicated the little importance of this contribution.[16] The coefficient α was determined from the measured values of radiation energy E_0 and E_1 at the beginning and end of the propagation path L; $\alpha = -1/L(\ln E_1/E_0)$. For the CO_2-laser radiation throughout the variation range of pulse duration the condition $I_{sat} < I_w < I_{op}$ holds true. Here $I_{op} \sim 10^7–10^8$ W/cm^2 (Ref. 17) is the threshold of optical breakdown of the atmosphere initiated by solid particles.

The causes of optical nonlinearity of atmospheric channel of HPLR propagation are mainly the processes resulting in evaporation, combustion, explosive destruction, change of shape and temperature of aerosol particles, optical breakdown of the ambient air.[3]

The liquid-droplet meteorological formations (fog, drizzle, rain) are known the natural filter cleaning the atmosphere from the solid-phase aerosol.[18] The degree of cleaning depends on the lifetime of the water-droplet filter. For example, for the case of fog this statement is well illustrated in Fig. 1. An indicator of presence of a solid-phase aerosol in the HPLR channel is the atmospheric optical breakdown initiated by particles with the radius $a_s \geq 10^{-4}$ cm. It is evident that in due course after the fog formation the number of breakdown sources decreases considerably. As half an hour passes, we do not observe the growth of the number of plasma sources in HPLR beam channel with the radiation energy increase. This fact is indicative of a marked decrease of coarse fraction of solid-phase aerosol in the atmosphere. In this case, the liquid-droplet component of aerosol filling of HPLR propagation medium remains the same. The figure shows the set of points, which gives no more than 20% of the obtained data for a specific meteorological state of the atmosphere. The coincident or adjacent points are not shown.

The principal nonlinear effect, influencing the variation of the medium extinction coefficient at propagation of high-power CO_2-laser pulses with intensity lower than breakdown values in water aerosol, is the explosive destruction of particles.[19,20] Droplets explode when the temperature inside a particle becomes close to the spinodal temperature that at standard water pressure corresponds to the temperature $T_{ex} \sim 593$ K (Ref. 21). At such overheatings, water vapor bubbles are actively generated in energy release zones inside a droplet; just these bubbles cause destruction of a whole droplet or its surface layers into smaller particles and water vapor. Depending on the particle size and the power parameters of radiation, the explosion process may be of single or multiple type. In both cases, explosion boiling up occurs, namely, the vapor emission from the zone of initial metastable overheating.

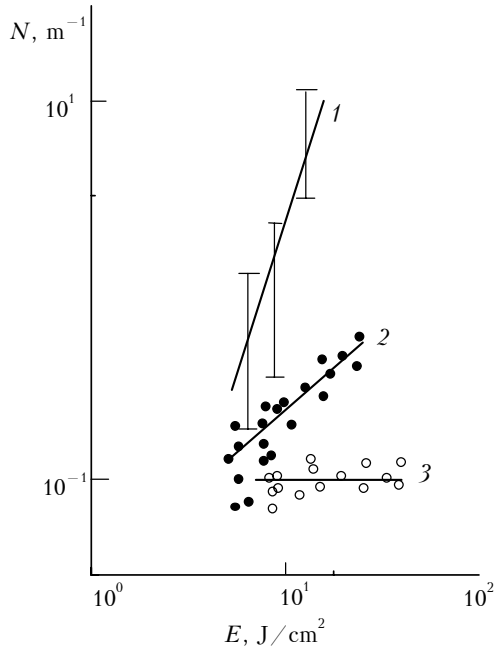

FIG. 1. Linear concentration of optical breakdown sources vs. laser radiation energy density: natural atmosphere without fog[2] (1); 15-min lifetime of a fog at the propagation path (2); 30-min lifetime of a fog at the propagation path (3).

To determine the coefficient α of HPLR extinction by the volume of destruction products of a fixed-size water droplet, evolution of this volume shape, the size of secondary particles and their concentration must be known. We have conducted the experimental and theoretical studies of the process of HPLR interaction with the droplet medium, which results point to the existence of the following regularities in the optical pattern of explosive destruction of a particle.

For small-particle aerosol ($2a\alpha_{ab} < 1$, where α_{ab} is the coefficient of radiation absorption by a droplet matter, a is the initial droplet radius) the quasi-homogeneous particle heating occurs. The explosion begins when radiation energy density exceeds the threshold value E_{ex}. This value depends slightly on the particle size and, as the experimental studies show, equals approximately 1.5–2 J/cm^2 (Ref. 22). Before and after the explosion, the aerosol particles and the condensed fraction of explosion products undergo the surface evaporation, which mode depends largely on the particle size and the radiation parameters. The obtained results point to the following dependence of $\alpha(E)$:

$\alpha = \alpha_0 (1 - u_1)$, $e \le E_{ex}$,

$\alpha = \alpha_0 (1 - u_{ex})$ e. p $[-\beta(d)(E - E_{ex})]$, $E > E_{ex}$.

Here $\alpha_0 = \pi N_0 \int_0^\infty f_0(a)\, a^2 K(a)\, da$, where N_0 is the initial particle concentration with the distribution function $f_0(\alpha)$; K is the factor of efficiency of radiation extinction by aerosol particle; $X_{ex} = M_v/M_0$ is the evaporation degree under explosion conditions (M_v is the mass of vapor generated at the explosion as a result of surface and volume vaporization; M_0 is the initial droplet mass); X_1 is the degree of droplet evaporation up to explosion boiling up at the pulse action ($X_1 \cong 0.01$); the parameter β characterizes the evaporation rate of secondary particles; $d = a/a_i$ is the destruction degree (a_i is the typical particle size of condensed fraction of destruction products). The numerical calculations indicate that, when d varies from 10 to 25, the evaporation efficiency of secondary particles decreases ($\beta \sim 0.14$–0.07 cm^2/J) due to smaller size of crushing products and the lower efficiency of laser radiation absorption by these products. Figure 2 presents the results of calculations and the laboratory experimental data for fine-drop fog (*1*) with $a = 2.7 \cdot 10^{-4}$ cm.

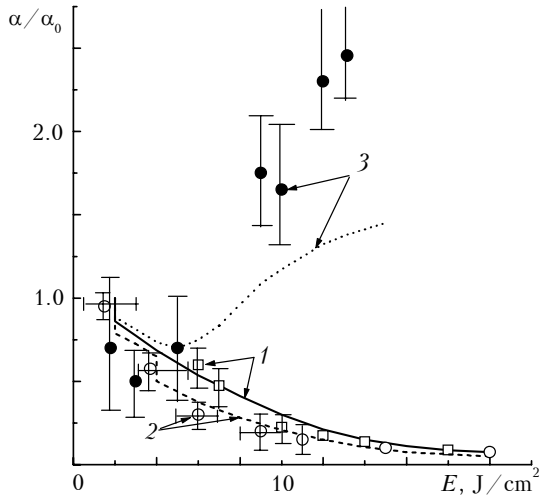

FIG. 2. Extinction coefficient of liquid-droplet meteorological formations vs. the HPLR energy density: monodisperse water aerosol (1); polydisperse water aerosol (2); natural atmosphere with rain (3).

The increase in the part of large fraction ($a > \alpha^{-1}_{ab}$) in the unperturbed aerosol size spectrum results in the fact that not all the volume of large droplets interacts with the radiation but those regions where the maximum heat release is localized, mainly in the illuminated and shadow hemispheres of particles. Formation of such regions is initiated by light field inhomogeneity inside particles.[23] For the energy threshold of the particle explosive boiling up at pulse heating, the following relationship

$$\alpha_{ab}\, e_{ex}\, V_{ef} = \int_{V_{ef}} \rho\, C_p\, (T_{ex} - T_0)\, dV$$

is valid, where V_{ef} is the total volume of zones of maximum heat release; ρ and C_p are the liquid density and the isobaric specific heat, respectively; T_0 is the initial temperature of the particle. If T is assumed equal to T_{ex} inside V_{ef} and temperature dependence of the product (ρC_p) is neglected, then $E_{ex} \cong \rho C_p\, (T_{ex} - T_0)/\alpha_{ab}$ and E_{ex} does not depend on the particle initial size. This fact testifies that, to describe the phase explosion process of particles with size $a > \alpha^{-1}_{ab}$, the threshold relations for finely dispersed aerosol can be used, but taking into account that the explosive boiling up occurs not in the entire droplet volume V_0, but in some its part V_{ef}. The value of V_{ef} can be estimated if we consider that all the absorbed energy in particle is used for heating of the volume V_{ef}: $\pi a^2 K_{ab} E \cong \alpha_{ab} E V_{ef}$, where K_{ab} is the efficiency factor of radiation absorption by a particle. In what follows, the unheated part of the volume $(V_0 - V_{ef})$ may be destroyed into large fragments ($a_i \le a/2$) or may form a new particle of lesser radius due to the surface tensile forces. In both cases, if the condition $E > E_{ex}$ holds true, the new series of explosions is possible. The experiments indicate that for the droplets with $a > \alpha^{-1}_{ab}$, $E_{ex} = 3$–5 J/cm^2 (Ref. 24). This threshold exceeds the corresponding value for finely dispersed aerosol. The threshold values point also to the possible use of the double explosion model, i.e. when the energy absorption no less than $2E_{ex}$ takes place

$$\alpha = \alpha_0(1 - u_1), \qquad E \le E_{ex};$$

$$\alpha = \alpha_{0f}\, (1 - u_{ex1})\, \exp\, [-\beta_1(E - E_{ex})] + \alpha_k,$$

$$e_{ex} \le E \le 2E_{ex};$$

$$\alpha = \alpha_{0f}(1 - u_{ex1}) \times \exp\, [-\beta_1(E - E_{ex})] +$$

$$+ \alpha_k(1 - u_{ex2}) \times \text{e. p}\, [-\beta_2(E - 2E_{ex})], \quad e > 2e_{ex}.$$

Here α_{0f} is the initial extinction coefficient of the fine fraction of initial aerosol with the distribution function $f_0(a)$; $\alpha_k \cong \pi N_0 \int_{a_k}^\infty f_0(a)\, K(a)\, a^2\, da$ is the extinction coefficient due to "nucleiB remaining after the first explosion, $a_k \cong 1/(2\alpha_{ab})$. The calculated dependence $\alpha(E)$ at explosion of polydisperse aerosol particles is given in Fig. 2 (curve *2*). The parameters of the initial Γ-distribution are: $\alpha_m = 5 \cdot 10^{-4}$ cm; $\mu = 3$. The particle size of polydisperse aerosol used in laboratory experiments is the following: $\overline{a} = 2.5 \cdot 10^{-4}$ cm; $\overline{a^2} = 2.9 \cdot 10^{-4}$ cm; $\overline{a^3} = 3.4 \cdot 10^{-4}$ cm.

In large droplets ($a \gg \alpha_{ab}^{-1}$), the distribution of heat sources is well described by the Bouguer law. In this case, V_{ef} is the volume of surface layer of the illuminated hemisphere of a particle. Therefore the explosion process of a large droplet can be represented as a succession of separate phases, namely, heating and boiling up of the surface layer; its flying away from a cold core nucleus; heating and boiling of the following surface layer, and so on. This allows description of the explosion of every isolated layer within the framework of the homogeneous absorption model. The extinction coefficient of coarse-disperse aerosol after explosion of jth surface layer can be written as

$$\alpha = \alpha_s + \alpha_n, \quad jE_{ex} \le E \le (j+1)E_{ex},$$

where $\alpha_s = (3/2)\,\alpha_{ab} N_0 (1 - u_{ex}) \sum_{i=1}^{j} \exp[-\beta(d_i) \times (E - ie_{ex})] \int_0^\infty f_0(a)\, V_{ef}^i \, da$

is the extinction coefficient due to secondary particles formed by j exploded surface layers; V_{ef}^i is the volume of the ith layer;

$$\alpha_n = 2\pi N_0 \int_0^\infty f_0(a)\, a_j^2(a)\, da$$

is the extinction coefficient due to "nuclei"; $a_j = (a_{j-1}^3 - 3V_{ef}^{j-1}/4\pi)^{1/3}$. Figure 2 presents the calculated dependence $\alpha(E)$ for large-droplet aerosol (curve *3*) modeled by Γ-distribution with the parameters $a_m = 7 \cdot 10^{-2}$ cm, $\mu = 1$. Similar aerosol spectrum is characteristic of rain.[25] The points are for the data of the field experiment. In contrast to the cases considered previously, in the case of rain, the extinction coefficient increases at exceeding the explosion boiling up threshold after some growth of medium transmittance due to vaporization of large droplets. This increase is caused by the growth of light scattering when dividing large particles.

3. IDENTIFICATION OF PROCESSES OF HPLR INTERACTION WITH AEROSOL AT FIELD END-SCALE PATHS AND UNDER LABORATORY CONDITIONS

The problems arising when interpreting the experimental data obtained under field conditions are connected with the impossibility of monitoring the HPLR beam parameters and the aerosol characteristics varying at interaction with beams at any required point of the propagation path. This brings up the necessity of remote assignment of physical processes occurring at HPLR interaction with aerosol particles in real atmosphere and determining the value of HPLR attenuation to the processes known from laboratory practice. The development of such methods is based on some requirements including remote character, lack of external distortions of the HPLR beam and the medium characteristics, high sensitivity to change of the process characteristics.

At present, the processes of HPLR interaction with aerosol of different chemical and phase composition, which can be described quantitatively and are suitable for remote indication of such interactions in real atmosphere, have been studied under controlled laboratory conditions. Such processes include, first of all, the phase transitions of liquid-droplet aerosol[19] and the optical breakdown developing on particles of solid-phase aerosol.[7,26]

The most important indication characteristics of these processes are generation of acoustic waves and variation of aerosol scattering characteristics at phase explosion of particles in the pre-threshold (with respect to the optical breakdown) mode. Higher acoustic pressures occur when the optical breakdown develops. Besides, in the case of development of a plasma source, the possibility of process visualization appears. The microphysical basis for development of the identification methods is in the study of behavior of the above-mentioned indication characteristics in different controlled conditions with varying HPLR energy. It is given in detail in Refs. 7 and 27–30.

The field investigations with different instrumentation on remote detection of indication characteristics have shown that it is profitable to use the optoacoustic method for identification of the processes.

Figure 3 demonstrates the agreement between the data of the field and laboratory experiments. From the experimental data obtained under field conditions, we select the aerosol situations corresponding to small-droplet aerosol fraction (fog) and the HPLR energy density, which does not provide the breakdown phenomena at the path.

Figure 3 compares the values of acoustic energy emitted by a separate droplet of fog in the course of explosion in the laboratory and field experiments. In the laboratory studies, the concentration of monodisperse particles with $a = 2.7 \cdot 10^{-4}$ cm was determined from the optical measurements.[27] In the open atmosphere, the particle concentration was determined from the fog water content.[31] The volume of the sound-emitting region was determined from acoustic measurements. Possible errors of HPLR energy measurement along the field path are given by horizontal bars. The lower value of W_{ac} in the field investigations at $E = 2\,\mathrm{J/cm^2}$ can be explained by availability of coarse-disperse fraction of particles in fog, for which the threshold conditions of explosion were not reached.[24]

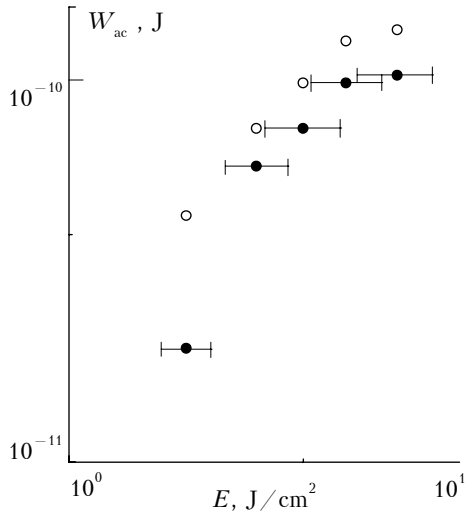

FIG. 3. Acoustic energy emitted at explosion of a separate droplet vs. the energy density of acting radiation: open circles is for laboratory conditions with monodisperse aerosol with size $a = 2.7\ 10^{-4}$ cm; *closed circles are for natural atmosphere with fog.*

At the early stage of existence of liquid-droplet meteorological formations on the path, when the atmosphere is not yet cleared of solid state aerosol particles, the plasma sources start their development at these particles at exceeding the corresponding energy threshold. The measurements have shown that the acoustic energy emitted by a separate plasma source greatly exceeds the energy emitted in water droplet explosion and reaches 10^{-3} J. It was established that a plasma source develops in the HPLR beam, as a rule, in the mode of light detonation wave.[7] The characteristics of a plasma source in this case are determined mainly by processes of gas heating in the absorption wave and depend slightly on the particle material properties. At the same time, the number of plasma sources arising in the HPLR beam is defined by the radiation energy, aerosol concentration and microstructure.

In the field experiments, the number of plasma sources at the path was determined simultaneously by photorecording and time-resolved reception of acoustic signals from separate sources. When analyzing the data of field experiments, the cases were selected with the values of HPLR energy density at the beginning of the path being different by no more than 10% from the averaged value over the all considered cases. These cases were accompanied by aerosol monitoring at the path. Comparison of the number of sources at the propagation path, found using photorecording and the acoustic method, indicated that the correlation coefficient is 0.89.

Thus, application of the acoustic method as accompaniment to experimental investigations of HPLR propagation in the open atmosphere makes it possible to determine the power modes of radiation interaction with aerosol particles and to use with confidence the whole set of experimental and theoretical results concerning optical consequences of such an interaction in the further interpretation of the data obtained.

4. EFFICIENCY OF HPLR ENERGY TRANSMISSION ON THE GROUND ATMOSPHERIC PATHS

Only few papers are devoted to the experimental investigation of HPLR energy attenuation at radiation propagation along the real atmospheric paths. Along with Refs. 2 and 4–10, Refs. 33–35 should be noted dealing with different aspects of the problem of HPLR interaction with the atmosphere. The results[33–35] were not analyzed in this paper due to the difference of optical and meteorological states of the atmosphere and the operating conditions of radiation sources.

Analyzed were the data of the field experiments, when HPLR energy was monitored at the beginning and at the end of propagation path; the standard meteorological parameters of the atmosphere were monitored, the side wind was lacking. The HPLR beam geometry remained invariant: $F/R \sim 9 \cdot 10^2$ (F is the focal length of the transmitting mirror telescope forming the radiation beam with the initial radius R). The aerosol component of unperturbed extinction coefficient of the atmosphere was determined according to Ref. 15. The components of gas constituent were calculated according to Ref. 14.

The complex analysis of the data on energy attenuation of a beam propagating along horizontal ground paths in real atmosphere, as well as the results of laboratory studies into the HPLR interaction with the dispersed media enabled us to propose the model for forecast of HPLR energy attenuation in liquid-droplet atmospheric formations. At this stage of investigations, most suitable is the graphic representation of the model in the form of dependence $H(\tau_0)$, Fig. 4*a*, and $H(E_f)$, Fig. 4*b*. Here $H = \Delta\tau/\tau_0$; $\Delta\tau = \tau_0 - \tau_n$, where $\tau_0 = \alpha_l L$ is the unperturbed optical depth of the propagation path, $\tau_n = \alpha_n L$ is the optical depth of the path after the HPLR pulse propagation; E_f is the HPLR energy density in the focal plane of the forming telescope neglecting atmospheric extinction characteristics.

Before using the model, needed is a knowledge of τ_0 for the moment of radiation start and the type of meteorological formation. The value of τ_0 can be calculated using the measured optical and meteorological parameters of the atmosphere[14,15] or can be obtained from the measurements of transmission of low-energy radiation with the wavelength coinciding with the HPLR wavelength. From the known value of τ_0, the parameter H is determined (Fig. 4*a*), and using Fig. 4*b*, the HPLR energy density level is established in correspondence with H. The excess over this level is undesirable for a specific type of meteorological formation. The error in determination of the HPLR transmission coefficient along the ground horizontal path does not exceed 25% and decreases with increasing lifetime of liquid-droplet meteorological formations.

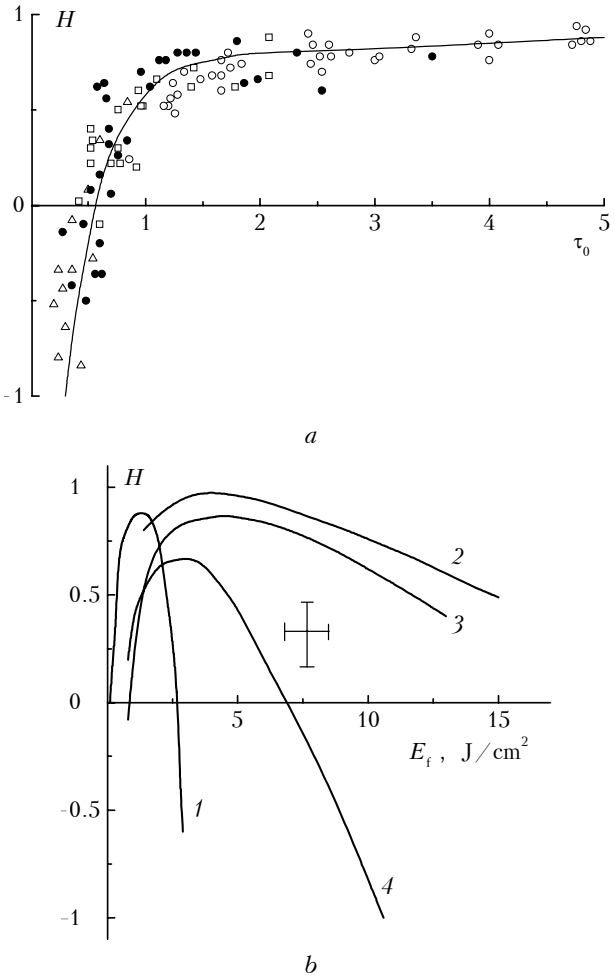

FIG. 4. Change of optical depth of the measurement path under the effect of CO_2-laser pulse vs. its initial value in different optical and meteorological situations (a) and energy density in the focal plane of the forming telescope for the same meteorological conditions (b): foggy haze (curve 1, closed circles), fog (curve 2, open circles), drizzle (curve 3, squares), rain (curve 4, triangles).

It is evident from Fig. 4 that there exist the critical energy densities, excess over which results in a considerable nonlinear attenuation of radiation. The value of the critical energy density increases with increasing optical depth of the propagation path. The peaks of the critical energy density are observed for the case of fogs, the minimum values are typical of weak rains and hazes.

CONCLUSION

Thus, the complex investigations of HPLR energy attenuation along the field path under conditions of foggy haze, fog, drizzle, rain and mechanisms of HPLR interaction with aerosol particles under controlled laboratory conditions have established the regularities of variation of the radiation attenuation coefficient at $\lambda = 10.6$ μm depending on the microphysical parameters of atmospheric aerosol and the radiation beam energy parameters.

The analysis of these regularities has made it possible to propose the model of engineering estimate of HPLR transmission for a specific optical and meteorological situation in the atmosphere. The basis for methodology of the model development is the confidence in adequacy of physical processes of HPLR interaction with aerosol under laboratory and field conditions established using the remote acoustic measurements. The model was tested along the horizontal ground path in the real atmosphere for the optical and meteorological conditions providing the initial optical depth up to $\tau_0 = 5$.

REFERENCES

1. I.Ya. Baranov, Kvant. Elektron. **21**, No. 6, 581–584 (1994).
2. Yu.V. Akhtyrchenko, E.B. Belyaev, Yu.P. Vysotskii, et al., Izv. Vyssh. Uchebn. Zaved., Ser. Fizika, No. 2, 5–13 (1983).
3. V.E. Zuev, A.A. Zemlyanov, and Yu.D. Kopytin, *Nonlinear Optics of the Atmosphere* (Gidrometeoizdat, Leningrad, 1989), 256 pp.
4. N.A. Blinov, I.A. Leont'ev, E.G. Ryzhkov, et al., Kvant. Elektron. **12**, No. 10, 2147–2149 (1985).
5. Yu.V. Akhtyrchenko, Yu.P. Vysotskii, S.L. Golub, et al., in: *Proceedings of the Institute of Experimental Meteorology*. IEM, Obninsk, (1986) issue 40(123), pp. 99–103.
6. M. Autric, C. Lefanconnier, and P. Vigliano, AIAA Pap., No. 1454, 1–9 (1987).
7. Yu.D. Kopytin, V.I. Kokhanov, V.A. Pogodaev, and S.A. Shishigin, Kvant. Elektron. **15**, No. 2, 405–411 (1988).
8. V.V. Vorob'ev, A.S. Gurvich, A.S. D'yakov, et al., Kvant. Elektron. **16**, No. 5, 1052–1054 (1989).
9. A.A. Zemlyanov, G.A. Mal'tsev, and V.A. Pogodaev, Atm. Opt. **2**, No. 6, 499–504 (1989).
10. Yu.E. Geints, A.A. Zemlyanov, and V.A. Pogodaev, Atm. Opt. **2**, No. 9, 798–803 (1989).
11. V.N. Aref'ev, Meteorol. Gidrol., No. 1, 97–112 (1980).
12. M.V. Kabanov, M.V. Panchenko, Yu.A. Pkhalagov, et al., *Optical Characteristics of Coastal Atmospheric Hazes* (Novosibirsk, Nauka, 1988), 201 pp.
13. A.A. Mitsel' and Yu.N. Ponomarev, *Optical Models of Molecular Atmosphere* (Nauka, Novosibirsk, 1988), 127 pp.
14. T.V. Blakhovskaya and A.A. Mitsel', in: *Laser Radiation Propagation in the Light Absorbing Medium* (IOA SB USSR AS, Tomsk, 1982), pp. 67–80.
15. V.L. Filippov, V.P. Ivanov, and N.V. Kolobov, *Dynamics of Optical Weather* (Kazan State University, Kazan, 1986), 157 pp.

16. V.A. Pogodaev, Atmos. Oceanic Optics **6**, No. 4, 211–213 (1993).
17. Yu.D. Kopytin, Yu.M. Sorokin, A.M. Skripkin, et al., *Optical Discharge in Aerosols* (Nauka, Novosibirsk, 1990), 159 pp.
18. L.T. Matveev, *Course of General Meteorology. Atmospheric Physics* (Gidrometeoizdat, Leningrad, 1976), 639 pp.
19. Yu.E. Geints, A.A. Zemlyanov, V.A. Pogodaev, A.E. Rozhdestvenskii, Optika Atmosfery **1**, No. 3, 27–34 (1988).
20. Yu.E. Geints, A.A. Zemlyanov, Atmos. Oceanic Opt. **6**, No. 11, 815–820 (1993).
21. V.P. Skripov, E.N. Sinitsin, P.A. Pavlov, *Thermophysical Characteristics of Liquids in Metastable State*, Reference Book (Atomizdat, Moscow, 1980) 208 pp.
22. A.A. Zemlyanov, M.F. Nebol'sin, V.A. Pogodaev, A.E. Rozhdestvenskii, Zh. Teor. Fiz. **55**, issue 4, 791–793 (1985).
23. A.P. Prishivalko, *Optical and Thermal Fields inside Light Scattering Particles* (Nauka i Tekhnika, Minsk, 1983), 190 pp.
24. Yu.V. Tolstikov, *"Processes of explosion destruction and secondary condensation when intense laser radiation influence water droplets and ice particles,"* Cand. Phys.-Math. Sci. Dissert., Obninsk (1987), 232 pp.
25. M. Steiner and A.I. Waldvogel, J. Atmos. Science **44**, No. 20, 3127–3133 (1987).
26. E.B. Belyaev, A.P. Godlevskii, Yu.D. Kopytin, et al., Pis'ma Zh. Tekh. Fiz. **8**, No. 6, 333–337 (1982).
27. N.N. Bochkarev, A.A. Zemlyanov, N.P. Krasnenko, et al., Pris'ma Zh. Tekh. Fiz. **14**, No. 1, 25–29 (1988).
28. N.N. Bochkarev, Yu.E. Geints, A.A. Zemlyanov, A.M. Kabanov, and N.P. Krasnenko, Opt. Atm. **1**, No. 10, 111–113 (1988).
29. N.N. Bochkarev, N.P. Krasnenko, and Yu.M. Sorokin, Atm. Opt. **3**, No. 6, 513–527 (1990).
30. A.A. Zemlyanov, Yu.E. Geints, A.M. Kabanov, and R.L. Armstrong, Appl. Opt. **35**, No. 30, 6062–6068 (1996).
31. *Atmosphere. Reference " ook* (Gidrometeoizdat, Leningrad, 1991), 509 pp.
32. S.V. Zakharchenko and A.M. Skripkin, Zh. Tekh. Fiz. **55**, No. 10, 1935–1942 (1985).
33. L.M. Vasilyak, S.P. Vetchinin, I.O. Kovalev, et al., Pis'ma Zh. Tekh. Fiz. **16**, No. 18, 1–4 (1990).
34. V.A. Banakh, V.M. Sazanovich, and R.Sh. Tsvyk, Atmos. Oceanic Opt. **8**, No. 3, 241–247 (1995).
35. A.I. Zhukov, D.Ya. Kovalevskii, and M.A. Fedorov, Atmos. Oceanic Opt. **8**, No. 10, 817–819 (1995).