NEAR-GROUND ATMOSPHERIC TRANSPARENCY FOR A PULSED CO_2 LASER RADIATION: CONDITIONS FOR A STABLE TRANSMITTANCE

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Received May 14, 1997

The results are presented from analysis of a field test data on the energy attenuation of the high-power laser radiation in the atmosphere. The conditions are identified for a stable atmospheric transmittance in different optical and meteorological situations.

The improvement in the performance of laser systems to be operated in real atmosphere is associated with an increase in the radiative energy parameters. Parameters in excess of certain threshold trigger nonlinear-optical processes along the beam path which distort the nominal beam parameters. The character and degree of distortions, as well as their physical mechanisms and the dynamics depend on the intensity of radiation, aerosol microstructure, wind velocity, turbulence intensity, etc.[1] In this connection, the development of optical systems for generating high-power laser radiation (HPLR) needs for preliminary assessments of their performance in real atmosphere under various meteorological conditions.

The effects of moist hazes and liquid-phase aerosols (fog, drizzle, rain) on the atmospheric transmittance for a pulsed CO_2-laser radiation, T_e, has been studied in Refs. 2–4 in detail. On the whole, two major processes of HPLR – aerosol interaction have been considered, namely liquid-phase aerosol evaporation yielding the clearing up of the impact volume and threshold appearance of the breakdown cells (BC) on the moistened evaporating particles which increase attenuation of HPLR. Moistening of solid-phase aerosol has little effect on the conditions favorable for break down in strong optical fields.[3] In contrast, the concentration of coarse fraction of solid-phase aerosol N_{cd} is much more important.[4] Liquid-phase constituents are known[5] to be a natural filter which clears up the atmosphere from the solid-phase aerosol. Washing out of the coarse dispersed fraction occurs on various timescales depending on the atmospheric optical and meteorological conditions (OMC) and disperse composition of liquid-droplet formations.

In this paper we discuss the results of analysis of the experimental data on the propagation of CO_2 laser pulses of microsecond duration in diverse aerosol formations (fog, drizzle, rain, snow) in the atmosphere. Studied is the effect of the impact period of these formations on the atmospheric extinction properties for HPLR. The analysis is motivated by the need to establish criteria of a reliable T_e forecast under various atmospheric OMCs.

The integrated measurements on the HPLR propagation under different OMCs included: determination of the beam path transmittance, photographic detection of the BC occurrence, sampling of the background aerosol disperse composition, and the recording of standard meteoparameters. Cross-beam wind was absent. The HPLR beam geometry $F/R = 9\cdot10^2$ was kept unchanged: (F is the focal length of the transmitting mirror telescope which collimates the laser beam to the initial radius R).

When the optical situation along the path is considered, it is important to know the lifetime of a given atmospheric OMC. In the measurement series conducted, we failed to cover OMC lifetime from its appearance to decay. Figure 1 illustrates the influence of a fog on N_{cd} in one of the measurement session.

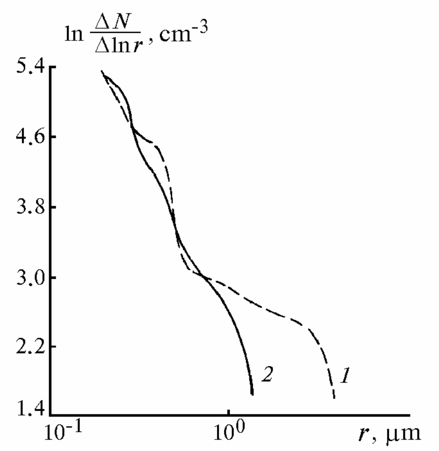

FIG. 1. Influence of a fog on the particle size distribution function: (1) disperse composition of aerosol particles 15 min *before the fog formation, (2) disperse composition* 15 min *after the fog decay.*

The order of appearance of the types of optical weather on the measurement path is as follows: 3-h long mist; fog (lifetime of 1 h and 10 min); mist. The changes in N_{cd} are significant. Consequences of such changes are depicted in Fig. 2.

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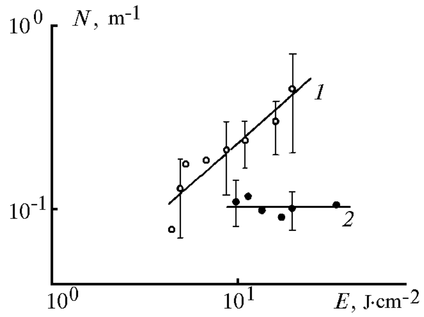

FIG. 2. Dependence of the linear concentration of optical break down cells on the laser radiation energy density: (1) 15 min *fog lifetime on the measurement path, (2)* 30 min *and longer lifetime.*

A quarter-hour long foggy situation decreases BC concentration due to HPLR pulse passage by an order of magnitude relative to the optical weather of the type of a spring or fall haze[6] (E = 10 J/cm^2). A half-hour or longer fog on the measurement path stabilizes the BC amount (hence, N_{cd}) within the HPLR energy range realized in the experiment. Plotted in Fig. 2 is a many-year data set. Absence of scatter in $N(E)$ values does not imply a single measurement, but rather this is indicative of the fact that there were three to five coincident measurements.

Figure 3 illustrates the influence of aerosol microstructure on the value of the nonlinear extinction coefficient (α_n) of the atmosphere for pulsed CO_2-laser radiation. Radiative energy density in the focal plane of the collimating telescope (E_f) did not exceed 20 J/cm^2. Extinction coefficient in the absence of nonlinearity in the medium of propagation (α_0) was determined from the atmospheric optical and meteorological conditions.[7] Curves are plotted using the least squares fitting. Error bars indicate the scatter of the experimental data.

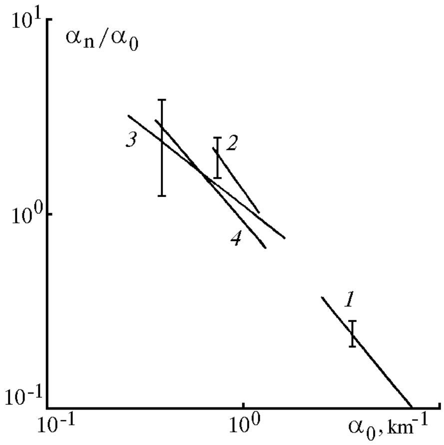

FIG. 3. Influence of the atmospheric optical and meteorological state on the nonlinear extinction coefficient for CO_2 *laser radiation: (1) fog, (2) drizzle, (3) rain, and (4) snow.*

For a fog, the ratio $A = \alpha_n/\alpha_0$ only slightly varies over the range of α_0 values realized in the experiment. The value A increases by no more than $5{\cdot}10^{-3}$ as the energy input to the medium increases by 1 J/cm^2.

As the liquid-phase aerosol (drizzle) increases in size, and hence its concentration decreases, the value A increases significantly up to ~2, for the same beam geometry and radiative energy as for the fog. The measurements of background aerosol size spectrum 0.5 h made along the path after the onset of drizzle indicate that the coarse dispersed fraction is less sensitive to this atmospheric OMC than to the fog. Period of continuous measurements in the experimental session realized under drizzle conditions did not exceed 40 min. During this, find the linear BC concentration in the HPLR beam channel dropped by a factor of 3–4 relative to the optical and meteorological situation preceding the drizzle, closely following the curve *1* in Fig. 2. Correspondingly, a 1 J/cm^2 increase in the energy input to the medium yields a $7{\cdot}10^{-2}$ increase in the A value.

Precipitation is the most variable atmospheric OMC in space and time. Observation sites separated by 1 km may give rainfall rates differing by a factor of 8 to 10.[5] In precipitation, the range of α_0 values realized in the experiment significantly widens toward smaller α_0 values. Analysis of the experimental data for a continuous rainfall at a rate I_r=1.5–3.0 mm/h shows that an averaged value A of 1 is approached in about 5 h. In a light precipitation (I_r < 1 mm/h), A ~ 1 is reached already in ~6 h. Conversely, at I_r ~ 15 mm/h, ~1 h suffices. The atmospheric extinction significantly increases with an increase of energy input to the medium. Table I illustrates this dependence for a 6-h time interval at I_r ~ 2.5 mm/h. Time from the onset of precipitation is ~2 h.

TABLE I. Influence of energy input to the medium on the nonlinear extinction coefficient for CO_2*-laser radiation in rain.*

A	1.95	2.45	2.95
E_f, J/cm^2	12.7	21.1	23

The shape of $A(\alpha_0)$ dependence and its numerical values are almost identical in a rainfall and a snowfall. At the same time a long situation with liquid-droplet meteoformations gives rise to a noticeable clearing up of the atmosphere from the background aerosol and to an increase in T_e, with a concurrent shot-to-shot T_e stabilization, while in the rainfall, $A(t)$ increases in the entire HPLR energy range realized. We have no data on the dependence of extinction coefficient on the snowfall rate, supported by the data on snowfall type and ice particle size distribution; we only know that extinction may vary by 0.92 km^{-1} at a 1 mm/h change in the snowfall rate.[8] Precipitation-induced extinction (λ = 10.6 μm), not giving rise to nonlinear effects, is nearly three times stronger in snowfalls of $I_s = 1$ mm/h than in a rainfall of $I_r = 5$ mm/h (see Ref. 9). This is because, snow particles falling slower than the rain drops have 3–4 times larger water content than a rain of the same rate.

For HPLR in liquid water and ice aerosol formations of the same optical depth, crystal aerosol will attenuate weaker.[10] That is why the value A decreases with increasing energy input and α_0=const. Moreover, more pulse energy is transmitted through a volume with a small-droplet aerosol[11] and in a medium with 50% mass of ice particles evaporated than in a crystal aerosol. In that case, variations of T_e, like those of N_{cd}, are determined by ice particle microstructure and snowfall intensity.

Now we consider the influence of the atmospheric OMC on T_e pulse-to-pulse stability, in the order of increasing aerosol particle size.

Fog. A widely used characteristic of a fog amount is the meteorological visibility range S_m.[5] A complete repeatability of T_e values in a fog for different HPLR pulses takes place under the following conditions: OMC exists for $t \geq 0.5$ h, E = const, S_m = const, time interval between pulses is no longer than 5 min. Also it is possible that, for measurement series performed in different years, or for HPLR pulses in one measurement series but separated by a considerable time interval with fixed values of E and S_m, the coincident T_e values are observed if an additional condition is satisfied – equal ambient temperatures (t_a) at times of HPLR pulses. Ambient temperature variations of 2°C lead to the T_e variations of up to ± 5%.

Drizzle. The available data of field tests were insufficient to establish T_e repeatability conditions at E = const. T_e stability within ±5% takes place under the following conditions: OMC exists for ~1 h, E = const, S_m = const, variations of relative humidity ≤ 3% and air temperature ≤ 2°C.

Rain. Necessary conditions for 5% stability of T_e in a rain at $I_r < 3$ mm/h are: E = const, S_m = const, I_r = const, washing-out time of the background aerosol (OMC life time) is 5 h. The stronger I_r, the shorter the washing-out time of the background aerosol, but the wider may be the range of variations of HPLR attenuation directly by raindrops over short time intervals, so that variance of T_e is much wider than 5%. Most favorable conditions for an increased HPLR transmittance are realized just after incessant rain (about one day-long precipitation). In this case, at E = const, there is absolute stability of atmospheric transmittance. The occurrence of such a situation will depend on wind conditions. At wind speed of $V = 1 - 2$ m/s, the enhanced transparency occurs for 0.5 h, on the average. At $V = 5 - 6$ m/s, 15–20 min will be sufficient for BC to appear and thus causing nonlinear extinction to develop.

Snow. T_e stability in a snowfall is impossible to determine by identifying E and S_m. *In situ* sampling of ice particle microstructure, knowledge of the $\alpha_0(I_s)$ dependence and spatial homogeneity of snowfall rate I_s are needed. According to data from Ref. 12, the snowfall rate is homogeneous to the distances of ~4–8 km.

Summarizing, the analysis of experimental data on HPLR attenuation in real atmosphere allowed us to identify conditions determining relative stability of the atmospheric transmittance for HPLR for different types of optical weather and unchanged initial radiative parameters. The uncertainty in the atmospheric transmittance in liquid-droplet aerosol formations is mainly caused by the presence of coarse dispersed aerosol fraction.

The urgency of the problem of reliable T_e prediction is significantly increased with the advent of mobile, autonomous HPLR sources of a wide utility and by the need to exploit them under different weather conditions.[13]

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