7. A. P. Boronin, Yu. A. Medvedev, and B. M. Stepanov, "Generalized electrical pulse and dynamics of dispersion of the products of a high-explosive charge explosion," Fiz. Goreniya Vzryva, No. 4, 541 (1973).
8. A. M. Prokhorov, S. I. Anisimov, and P. P. Pashinin, "Laser thermonuclear fusion," Usp. Fiz. Nauk, 119, No. 3, 401 (1976).

# DYNAMICS OF A SOLID MICROPARTICLE IN A PULSED LASER RADIATION FIELD

V. I. Bukatyi, V. A. Podogaev, and D. P. Chaporov

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The propagation of intense optical radiation in a medium containing a solid aerosol causes a number of thermal effects resulting in a change in the energetics and structures of the optical beam. Thus, turbidization of a medium containing solid microinclusions (soot conglomerates of the dimension $\sim(2\text{-}5)\ 10^{-4}$ cm) which increase with the increase in the power flux of the active radiation, has been detected in [1]. The authors of [1] assume that the main reason for the turbidization is the destruction of the soot conglomerates, however, the fractionation process itself was not investigated in detail.

The purpose of this paper is to study the dynamics of a single act of soot conglomerate destruction in a field of intense laser radiation and the investigation of certain characteristics of this process.

Experiments on the action of an intense laser pulse on individual aerosol particles were performed on the apparatus whose block diagram is shown in Fig. 1. Neodymium–glass laser radiation 1 of the type GOS-1001, with up to $10^3$ J energy operating in the free generation mode with the pulse duration $\sim(1\text{-}1.9)\ 10^{-3}$ sec and the wavelength $\lambda = 1.06$ $\mu$m was used as the active source. The powerful radiation was focused by the lens 2 with the focal length $F = 150$ cm into the working volume of the chamber 8 in which soot particles were dispersed by an air flow. The particles obtained were conglomerates of irregular shape with the mean effective diameter $\sim 5 \cdot 10^{-4}$ cm.

A signal from the FÉU-28 3 was supplied to the oscilloscope C 8-2 6 in order to determine the beginning of the action, and to check the duration and shape of the radiation pulse. The flow of the soot particles during the action was recorded at a 90° angle to the direction of propagation of the active radiation by using a FEU-28 7 from which the signal was supplied to the oscilloscope. To eliminate the influence of scattered radiation of the active laser, a filter with almost 100% reflection coefficient for $\lambda = 1.06$ $\mu$m was placed in front of the photomultiplier. The time of the beginning of action on the aerosol and the beginning of recording its glow on the oscilloscope was synchronized by using the delay module 5. The oscillograms characterizing the particle glow process in the channel and the pulse shape were photographed.

The energy of the active radiation was checked during the measurements by using the IMO-2 4.

Mounting of a photographic apparatus with a microphoto attachment in place of the FEU 7 permitted obtaining an integrated picture of the destruction of the soot particles. A typical photograph of the process is presented in Fig. 2. The arrow indicates the direction of the acting radiation. Photography yields a graphic representation of the dispersion diagram of the destruction products, an important characteristic in analyzing the transfer of optical radiation in aerosol media subjected to the effect of intense light pulses. The mean velocity of particle motion is $\sim 2 \cdot 10^2$ cm · sec$^{-1}$. It is interesting to estimate the contribution of the light pressure force and the reactive force, which govern during interaction between a powerful laser pulse and an aerosol, to the particle motion.

Let us estimate the velocity of the motion of an individual soot particle in a laser beam because of the light pressure force. The equation of particle motion in air can be written in the form [2]

$$F_p + F_d = M dv/dt, \quad (1)$$

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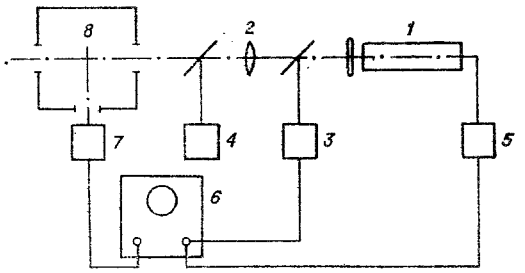


Fig. 1

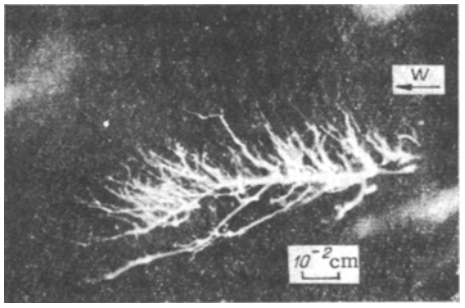


Fig. 2

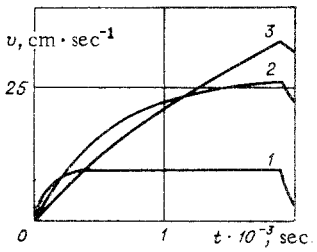


Fig. 3

where $M=(4/3)\pi r^3\gamma$ is the particle mass, v is its motion velocity, r, $\gamma$ are the effective radius and density of the particle material, respectively, $F_d=-6\pi r\eta v(1+(1/6)\mathrm{Re}^{2/3})$ [3] is the drag, and $\eta$ is the dynamic viscosity of the medium. The formula for $F_d$ works well for the Reynolds numbers $\mathrm{Re}\lesssim 300$. For our case $\mathrm{Re}\sim 1$, therefore, the second member in the parentheses can be neglected. According to [4], the light pressure force is $F_p=(\pi r^2/c)WK_p(\rho, m)$ where c is the speed of light, W is the incident radiation flux density, $K_p$ is the light pressure cross section, $\rho$ is the Mie parameter, $m=n-i\varkappa$ is the complex refractive index of the particle material, n is the coefficient of refraction, and $\varkappa$ is the absorption index.

We do not take account of motion under the effect of gravitation. It is sufficient to state that the path traversed by the soot particles of radius $\sim 5\cdot 10^{-4}$ cm under the effect of gravitation during the action of the effective pulse ($t_p=1.9\cdot 10^{-3}$ sec) is $1.1\cdot 10^{-3}$ cm.

Taking the above into account, (1) can be rewritten as follows:

$$dv/dt + 9\eta v/2r^2\gamma = 3WK_p/4cr\gamma. \tag{2}$$

For the initial conditions t=0, v=0, the solution of (2) has the form

$$v=\frac{WK_p r}{6c\eta}\left[1-\exp\left(-\frac{9\eta t}{2r^2\gamma}\right)\right].$$

A dependence of the velocity of soot particle motion on the time in the radiation field is presented in Fig. 3. Curve 1 corresponds to the value $r=2\cdot 10^{-4}$; 2 to $5\cdot 10^{-4}$; and 3 to $10^{-3}$ cm; $W=1.62\cdot 10^5$ W · cm$^{-2}$, $\gamma=1.82$ g · cm$^{-3}$ [5]. The quantity $K_p$ was obtained by extrapolating the dependence $K_p(\varkappa)$ [6] for the conditions of the experiment: $m=1.9-1.02\cdot i$ [5] for the acting radiation wavelength $\lambda=1.06$ $\mu$m. The values of $K_p$ found are 1.03, 1.18, and 1.26, respectively, for curves 1-3.

After cessation of the action of the radiation pulse, the velocity of particle motion is described by the formula

$$v_1 = ve^{-t/\tau_r}$$

where $v_1=v$ at the time of termination of the laser pulse, and $\tau_r=2r^2\gamma/9\eta$ is the relaxation time for the velocity of a particle of radius r.

Besides the effect of the light pressure force, absorbing microparticles of material placed in a beam of intense laser radiation will experience unilateral evaporation. The particles can acquire the velocity [7]

$$v = v_e\ln(M_0/M(t)), \tag{3}$$

in such evaporation, where $v_p$ is the velocity of escape of the material vapor, $M_0$, M(t) are the initial and running mass of the particle, respectively. It is necessary to know $v_p$ when making estimates by means of (3). To determine the maximum value of this quantity, an expression of the form [8]

$$v_{e\,max} = (W/mj_m)^{1/2},$$

can be used, where m is the mass of gas atom in whose medium the evaporation occurs, $j_m = W/\varepsilon(1 + 2.2kT_0/\varepsilon)$; $\varepsilon$ is the crystal lattice binding energy, $T_0$ is the surface temperature, and k is the Boltzmann constant. For a W not exceeding $10^{10}$ W·cm$^{-2}$ in order of magnitude, (for graphite $7.7 \cdot 10^{10}$ W·cm$^{-2}$), the process is described by the thermal mechanism of destruction and $T_0 \sim \varepsilon/k$ [8]. In this case the expression for $v_{p\,max}$ takes the form $v_{p\,max} = (3.2\varepsilon/m)^{1/2}$. Assuming $\varepsilon \sim 10^{-12}$ erg, we obtain $v_{p\,max} \sim 8 \cdot 10^5$ cm·sec$^{-1}$. The corresponding value of v according to the relationship (3) is $5.6 \cdot 10^4$ cm·sec$^{-1}$, which significantly exceeds the experimental value of v obtained in this paper.

According to [1], the temperature of the sooty particles exposed to an optical radiation pulse will fluctuate around the boiling point of the material ($T \sim 3800$°K) in the case being realized. At the same time, combustion of the particles already occurs for $T \sim 900$°K and the destruction process starts in the fragmentation mode. The secondary particles (the destruction products $\sim 10^{-4}$ cm) have different velocities from the velocity of the vapor escape since the viscous medium drag acts on them. The estimates presented in [8] yield the value of the velocity of such particles $\sim 10^3$ cm·sec$^{-1}$. Taking this into account we find the reactive velocity of particles experiencing a partial drop in the mass from (3), which is $\sim 70$ cm·sec$^{-1}$, and is in good agreement with the experimental results. Therefore, the motion velocities of sooty microparticles due to reactive forces and the light pressure force agree in order of magnitude, and are added in this case.

For coarse particles $\sim (15\text{-}20) \cdot 10^{-4}$ cm the absence of complete destruction during the pulse is characteristic for power flux densities of the effective radiation of $1.6 \cdot 10^5$ W·cm$^{-2}$. The particle is pulverized into polydispersed products with a dimension from the submicron to $(5\text{-}10) \cdot 10^{-4}$ cm. Destruction products of the dimension $\sim 5 \cdot 10^{-4}$ cm traverse a path in the medium not less than 1.5 cm while a particle in a viscous medium will traverse a distance not exceeding 0.5 cm at medium motion velocities $\sim 2 \cdot 10^2$ cm·sec$^{-1}$ during a pulse with the path traversed during the relaxation time taken into account. This indicates that coarse particles $\sim (15\text{-}20) \cdot 10^{-4}$ cm move at the velocities $\sim 10^3$ cm·sec$^{-1}$, which can be achieved because of the more intense destruction and the absence of decelerating ejections from the shaded side [9]. It must be noted that the combustion of the products ceases after termination of the pulse and total destruction of the corase conglomerate does not occur. This circumstance contributes to turbidization of the propagation track over the extent of the whole pulse of effective radiation, as well as a certain time after termination of the pulse.

Therefore, because of the experiments conducted, particle tracks were recorded in the chamber during the action of powerful laser radiation, from an analysis of which the deduction can be made that particles are accelerated in the chamber and pulverized. Values of the double angle of dispersion of the dissociation products are $\sim 90°$ from the direction of propagation of the radiation (see Fig. 2). It can be concluded on the basis of processing the oscillograms that the particle glow starts with a lag on the order of $4 \cdot 10^{-6}$ sec relative to the beginning of the action. The first 2-3 beams heat the particle, it starts to glow, then the glow intensity drops 1.5 times. The half-width of the first beam of the glow is $\sim 15 \cdot 10^{-6}$ sec. Later, a 50% modulation of the light intensity is observed. This can be explained by the shielding of the main nucleus of the conglomerate by the destruction products [9]. The glow intensity grows, reaches a maximum, and drops to zero in the time $\sim 350 \cdot 10^{-6}$ sec. The glow is later absent although energy pumping continues, which indicates the predominance of particles with small dimensions which have a low coefficient of absorption [10], up to the end of the pulse action.

Comparing the particle tracks and the glow oscillograms for different power density levels in the channel permits making the deduction that the lifetime of the whole conglomerate diminishes as the power density of the incident radiation increases. Thus for the power densities $1.3 \cdot 10^5$, $1.13 \cdot 10^5$, $0.7 \cdot 10^5$ W·cm$^{-2}$ the track lengths 0.1, 0.15, 0.4 cm are respectively obtained. The glow times corresponding to the particle lifetimes are $0.6 \cdot 10^{-3}$, $1.0 \cdot 10^{-3}$ and $1.2 \cdot 10^{-3}$ sec.

The fluctuating nature of the particle motion is observed for the value $0.7 \cdot 10^5$ W·cm$^{-2}$ of the power density; this indicates that a recoil pulse occurs at the time of pulverization which forces the main particle to change the direction of its motion. The period of the ejections of the destruction products is $\sim 0.8 \cdot 10^{-3}$ sec for the mentioned value of the power.

The particle velocity in the channel can be estimated by means of the track length and the glow duration for different densities of the effective radiation, under the assumption of uniform motion. Thus, for $r \sim 2.5 \cdot 10^{-4}$ cm we have $v \sim 1.5 \cdot 10^2$ cm·sec$^{-1}$ for $W = 1.3 \cdot 10^5$ W·cm$^{-2}$ and $v \sim 3 \cdot 10^2$ cm·sec$^{-1}$ for $W = 0.7 \cdot 10^5$ W·cm$^{-2}$, from which the deduction can be made that for high levels of energy pumped into the channel, the main part of the particles ($r \sim 2.5 \cdot 10^{-4}$ cm) is decelerated during destruction. The integrated curve of the destruction presented in Fig. 2 indicates this circumstance.

## LITERATURE CITED

1. V. I. Bukatyi and D. P. Chaporov, "Dynamics of solid aerosol transparency during interaction with a laser radiation pulse," in: Fourth All-Union Symposium on Laser Radiation Propagation in the Atmosphere. Abstracts Reports [in Russian], Tomsk (1977).
2. V. I. Bukatyi and Yu. D. Kopytin, "Effect of light pressure on the transparency of a polydispersed aerosol," Izv. Vyssh. Uchebn. Zaved Fiz., No. 6 (1971).
3. L. T. Matveev, Physics of the Atmosphere [in Russian], Gidrometeoizdat, Leningrad (1965).
4. K. S. Shifrin and I. L. Zel'manovich, "Light pressure on water drops," Opt. Spektrosk., 17, No. 1 (1964).
5. G. H. Chan, "Effective absorption for thermal blooming due to aerosols," Appl. Phys. Lett., 26, No. 11 (1975).
6. K. S. Shifrin and I. L. Zel'manovich, Light Scattering Tables [in Russian], Vol. 3, Gidrometeoizdat, Leningrad (1968).
7. G. A. Askar'yan and E. M. Moroz, "Pressure during evaporation of material in a radiation beam," Zh. Eksp. Teor. Fiz., 43, No. 6 (1962).
8. S. I. Anisimov, Ya. A. Imas, G. S. Romanov, and Yu. V. Khodyko, Effect of High-Power Radiation on Metals [in Russian], Nauka, Moscow (1970).
9. V. A. Pogodaev, "Effect of $CO_2$ laser radiation on solid microparticles," in: Second All-Union Symposium on Laser Radiation Propagation in the Atmosphere, Abstracts of Reports [in Russian], Tomsk (1973).
10. A. G. Blokh, Thermal Radiation in Boiler Installations [in Russian], Énergiya, Leningrad (1967).


# COMPUTATIONS OF THE GAIN COEFFICIENTS OF MULTICOMPONENT WORKING MEDIA IN COMBUSTION-PRODUCT $CO_2$ GDL


A. P. Genich, N. V. Evtyukhin, S. V. Kulikov, G. B. Manelis, and M. E. Solov'yeva



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That the real laser working medium is a multicomponent medium [1] must be taken into account in producing powerful $CO_2$ gasdynamic lasers (GDLs) operating on combustion products. Numerical computations, in addition to the experimental investigations, play an important role in this area. Such computations permit a better conception of the mechanism of population inversion formation in the flow and insofar as is possible the replacement of a tedious experiment.

The optical gain coefficients of complex working media whose compositions are adequate to the compositions of propellant combustion products from the elements C, H, O and N are considered in this paper. The analysis and classification of the results are performed on the basis of an examination of the element composition of the working medium since the atomic composition, the temperature $T_0$, and the pressure $p_0$ of the gas in the reservoir uniquely determine all its thermodynamic characteristics: the equilibrium components of the composition, the internal energy, etc. The mathematical model and the method of computation have been described earlier in [2]. In order to assess how correct the model used is, whether the kinetic constants needed to compare the computation results with the experimental data in a broad range of working medium compositions, stagnation parameters, and nozzle characteristics. In this connection, an attempt is made in the first two parts of the paper to select a set of vibrational relaxation rate constants that would permit matching the computational and available experimental results in the best way.

1. Flow of a mixture of the gases $CO_2$, $N_2$, and $H_2O$ through a nozzle was examined. The formulation of the problem and the computation method are presented in [2]. Since the computations were performed for $T_0 < 2000°K$, then in all cases the chemical processes were not taken into account. In contrast to [2], an implicit difference scheme with an almost second-order approximation ($s = 0.44$) [3] was used, which permitted shortening the computation time.


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