PROPAGATION OF HIGH–POWER LASER RADIATION IN A MONODISPERSE SOL IN VACUUM

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Interaction of a powerful laser radiation with high–melting sol particles in vacuum is considered. The volume extinction coefficient has been found for a monodisperse sol at its gas–dynamic vaporization taking into account the recondensation based on the results from Refs. 2 and 3.

Propagation of a high–power radiation with power density of 10^9 W/m^2 through a disperse media of high–melting particles can cause heating of the latter to the temperatures[1] 3000–5000 K. At such a high temperature the pressure of saturated vapor of the evaporating particle substance becomes significantly greater than the atmospheric pressure. Under these conditions removal of a vaporized substance away from the particle surface occurs at a supersonic speed, and the application of the diffusion model becomes impossible. A gasdynamic model of vaporization of an individual high–melting particle in the high–power laser field in vacuum has been proposed in Ref. 2. This model makes it possible to calculate the thermodynamic vapor characteristics taking into account its recondensation and formation of the cloud of secondary particles. Size distribution function (SDF) of secondary particles, as well as the size of secondary particles themselves as a function of the distance from the primary particle have been obtained in Ref. 3 based on the results from Ref. 2.

This paper deals with the volume extinction coefficient of a disperse medium containing the high–melting particles in vacuum being vaporized under the action of radiation taking into account recondensation.

Let us assume that all the primary particles have one and the same size, i.e., it is a monodisperse sol which is described by the SDF in the form of δ–function

$$f_1(a, z) = n(z)\,\delta(a - a_0(t)) , \qquad (1)$$

where $n(z)$ is the number of primary particles per m^3 at the distance z from the radiation source along the direction of propagation of electromagnetic wave with the density of energy flux I and $a_0(t)$ is the time–dependent radius of an evaporating particle.[4]

Let us also assume that the number of primary particles is quite small so that they do not influence on each other during vaporization, and that the vaporization of all particles starts simultaneously. In addition, let us neglect the particle motions under the action of light pressure and consider the statistical model of aerosol.

In the single–scattering approximation the equation describing the behavior of the density of energy flux I of the incident radiation in the "primary + secondary particles" system is written in the form

$$\frac{dI(z)}{dz} + \alpha(z)\, I(z) = 0 , \qquad (2)$$

where $\alpha(z)$ is the volume aerosol extinction coefficient of the primary and secondary particles so that the relation

$$\alpha = \alpha_1 + \alpha_2 \qquad (3)$$

is satisfied. Here α_1 and α_2 are the volume extinction coefficients of the primary and secondary particles, respectively.

According to Ref. 5, the relations for $\alpha_1(z)$ and $\alpha_2(z)$

$$\alpha_1(z) = \int_0^\infty \pi a_1^2 f_1(a_1, z)\, k_0(a_1, \lambda)\, da_1 ,$$

$$\alpha_2(z) = \int_0^\infty \pi a_2^2 f_2(a_2, z)\, k_0(a_2, \lambda)\, da_2 \qquad (4)$$

are valid. Here a_1, a_2, f_1, and f_2 are the size and SDF of primary and secondary particles, respectively and $k_0(a, \lambda)$ is the extinction efficiency factor.

The characteristic time of the change of the particle size due to its vaporization has been estimated in Ref. 1 for the density of energy flux of the incident radiation $I = 3{\cdot}10^9$ W/m^2. This time was about 10^{-4} s for $a = 10$ μm. The characteristic time of establishing the stationary fields of the thermodynamic parameters $t \sim a/\bar{v} \sim 10^{-8}$ s for $\bar{v} \sim 1000$ m/s, where $\bar{v}$ is the mean thermal speed of the vapor molecules. Therefore, the radius of a 10–μm particle changes insignificantly during the period of establishment the stationary fields. One can show that this regularity holds in a wide range of atmospheric aerosol size and densities of the energy flux $I \sim (10^7–10^{10})$ W/m^2. The problem in finding the distribution function of secondary particles have been solved in a quasistationary approximation in Ref. 3. Let us find the volume aerosol extinction coefficient of the secondary particles in the same approximation.

According to the gas–dynamic model[2] of the vaporization of a single high–melting particle, molecules of the vaporized substance can be in both the gaseous and condensed solid phase. The estimates presented in Ref. 2 showed that the size of the area of generation of nuclei of a new phase is about 10^{-6} m, and the characteristic time of the vapor spreading from the particle surface is approximately 10^{-8} s. Therefore, one can assume for the first approximation that the whole vapor surplus instantaneously condensates on the generated condensation nuclei in a very narrow region, and the vapor is in the thermodynamic equilibrium with the condensate.

As is shown in Ref. 3, the mass of the vaporized substance at a distance $\sim 20\, a_0$ from a particle becomes comparable to the mass of the primary particle, since here

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the particle free path becomes comparable with the particle size, and the speed of the vapor spread exceeds the sound speed in a gas. Then small particles have insufficient time for growth and spread farther with carbon vapor. The concentration of secondary particles in the area of the nuclei generation was found in Ref. 3 on the basis of introducing the vapor condensation degree as a function which characterizes a two–phase system and previous approximations. Thus, it is about 10^{21} particles/m^3 for a primary particle 10 μm in size. If the secondary–particles concentration is known at any distance r from the center of a primary particle, one can find their distribution function for the case of spherically symmetric vaporization of the particle. It has been obtained in the form[3]

$$F(a, r) = n(r)\,\delta(a - a(r)) , \qquad (5)$$

where $n(r)$ and $a(r)$ are the concentration and the size of secondary particles at the distance r from the primary particle. Then

$$\varphi(a) = \int_{a_0}^{20\,a_0} n(r)\,\delta(a - a(r))\,4\pi r^2\,dr \qquad (6)$$

is some SDF of particles generated by a single primary particle. The dimensionality of the function $\varphi(a)$ is 1/m, in contrast to the dimensionality of the SDF of primary particles. The upper limit of integration over r is chosen to be equal to 20 a_0 based on the estimates presented in Ref. 2.

Thus, by calculating integral (6) we obtain

$$\varphi(a) = n(r(a))\,4\pi r^2(a) , \qquad (7)$$

where $r(a)$ is the inverse function of the known function[3] $a(r)$. Let us note that since $a_0 \le r \le 20\,a_0$, in Eq. (7) a is in the range $a(a_0) \le a \le a(20\,a_0)$ and $a(a_0)$ is the initial size of a nucleus of a new phase. It is equal to the critical size[6] $a_{cr} = 10^{-9}$ m. Then the SDF of secondary particles has the form

$$f_2(a_2, z) = n(r(a_2))\,4\pi r^2(a_2)\,n(z) , \qquad (8)$$

and the expression for $\alpha_2(z)$ is written as follows:

$$\alpha_2(z) = n(z) \int_{a_{cr}}^{2a_{cr}} n(r(a_2))\,4\pi r^2(a_2)\,\pi a_2^2\,k_0(a_2, \lambda)\,da_2 , \qquad (9)$$

where the upper integration limit is chosen to be equal to 2 a_{cr} based on the data from Ref. 3.

One can find the solution for $\alpha_2(z)$ by the numerical integration, since the integrand contains the complex dependence on r in the function $n(r(a))$. Let the initial aerosol be composed of carbon particles with $a_0 \simeq 10$ μm and $n(z)$ is some constant value, for example, 10^8 m^{-3}, what corresponds to the condition of dusty air.

The extinction efficiency factor for secondary particles is found by the well–known calculation technique described in Ref. 5 for $\lambda = 10$ μm and the complex refractive index of carbon $m = 1.95 - i\cdot 0.66$. The concentration and size of secondary particles are known functions[3] of r. The integration gives the value $\alpha_2(z) \sim 10^{-5}$ m^{-1}.

One can write the following relation for $\alpha_1(z)$

$$\alpha_1(z) = n(z) \int_0^{\infty} \delta(a - a_0)\,k_0(a_0, \lambda)\,\pi a_0^2\,da_0 = n(z)\,\pi a_0^2\,k_0(a_0, \lambda), \qquad (10)$$

which results in $\alpha_1 \approx 6\cdot 10^{-2}$ m^{-1}, i.e., $\alpha_2(z)$ is about 100 times greater than $\alpha_1(z)$. Thus, the main contribution to the total volume extinction coefficient comes from the primary particles, while the secondary particles are practically optically inactive because of their small size.

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