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PREDICTION OF THE CHARACTERISTICS OF THE PROCESS OF INTERACTION OF PULSED LASER RADIATION WITH GASDISPERSE SYSTEMS

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Models of the process of interaction of pulsed laser radiation with gasdisperse systems are developed. Both individual stages of the process accompanying the interaction of a laser pulse with a gasdisperse system and the dynamics of the state of the system under the conditions of interference of processes of various physical nature are modeled. Generalized dependences allowing prediction of the characteristics of a probing beam are constructed. Boundaries of the region of efficient supply of laser-pulse energy to the system are determined.

The development of modern high-intensity technologies quite frequently requires that problems for which the universally accepted mathematical models are either absent or have not yet taken a final form be solved. One problem is that of interaction of pulsed laser radiation with gasdisperse systems.

The interaction of radiation with gas suspensions represents one method of energy supply to the working substance and the element of controlling action on gasdynamic and heat-and-mass-exchange processes. In certain situations, such an interaction is undesirable, since it leads to an attenuation of the characteristics of a probing or working beam. A search for conditions under which a reduction in the threshold value of the power of a laser pulse ensuring that realization of optical breakdown and the excitation of combustion and detonation in a gasdisperse mixture are possible is of interest for both problems of laser initiation of the processes and problems of safe transport of radiation through dangerously explosive mixtures.

For mathematical support of the problem it is necessary to create a coordinated system of models and to correctly represent the interrelation and interference of processes of various physical nature, which occur in a wide range of characteristic time and spatial-variable scales and develop against the background of the general gasdynamic evolution of the system. The presence of different-scale processes, on the one hand, allows simplification of the construction of a computational procedure by dividing the processes into rapid and slow ones, and on the other, it introduces certain difficulties in the numerical realization of the model.

The above factors determine the special properties of development of the aids of modeling of laser breakdown in gasdisperse systems. Reasonable use of a priori knowledge of the physics of the process allows simplification of the construction of the model and parametric investigations based on it.

Qualitative Pattern of the Occurring Processes. The presence of metal particles having fairly low values of the evaporation temperature and the ionization potential leads to a reduction in the threshold values of the laser breakdown of the medium as compared to the threshold of breakdown in a pure gas [1, 2]. For example, at t_i = 10^{-8}–10^{-6} sec and λ = 1 μm, the threshold intensity of laser radiation is $I_* = 10^8$–10^9 W/cm^2, whereas for a pure gas it is $I_* = 10^{11}$ W/cm^2. At λ = 10 μm, we have $I_* = 10^7$–10^8 W/cm^2 and $I_* = 10^{10}$ W/cm^2 for a pure gas.

The supply of energy to the system occurs in the form of a combination of interrelated processes of various physical nature [1, 2].

The initial contribution of energy is carried out on metal particles. The characteristics of heating of the particles depend on both the optical properties of the material of dispersed inclusions and the shape of the particles and their size in relation to the radiation wavelength. The heating of a particle is accompanied by phase transitions, includ-

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ing the transition of the particle's substance to a vapor phase. A vapor halo which contains a metal vapor heated to a high temperature is formed around the particle.

The vapor halo of the particle is the object of further energy contribution. Its ionization leads to a formation of free electrons which receive the energy of the electromagnetic field due to the inverse braking effect [2, 3]. When the energy of an electron exceeds the ionization threshold, we have impact ionization of a neutral particle. The mechanism of branching of chains leads to the formation of an electron avalanche, which results in the microplasma site near the particle.

The plasma becomes nontransparent to the radiation arriving at the focal volume and completely assimilated by the plasma formation. Growth in the pressure and extension of the high-temperature region occur, which leads to the formation of a system of shock and acoustic waves propagating in the space around the particle.

On further supply of energy, microplasma sites are extended due to the thermal diffusion of electrons into the regions adjacent to the vapor halo and the involvement of the molecules and atoms of the gas around the particle in the process of ionization. The microplasma sites unite into a single plasma formation [4].

The formation of high temperatures and pressures in the volume of the space-time field of laser radiation creates conditions for development of a detonation wave in the medium.

The above qualitative scheme of the process provides the basis for the creation of aids for mathematical modeling.

Micro- and Macrolevel Models. The construction of a mathematical model is based on the method of two-level modeling [5, 6], according to which the processes and corresponding models are divided into micro- and macrolevels.

The lower level corresponds to the processes occurring in interaction of radiation with individual particles and is the content of a microlevel problem [7, 8], whereas the upper level corresponds to the processes in the working space of the computational domain and represents a macrolevel problem. The micro- and macrolevel problems are related using iterative correlation in the computational procedure based on the idea of splitting by physical processes.

In constructing the macromodel of a medium, it is assumed that particles are uniformly distributed in the volume of the computational domain, and the region of space per individual particle is approximately represented by a spherical layer. The exterior surface is modeled as an impermeable adiabatic boundary by virtue of the equal interference of particles. Description of the processes in an individual chemical and hydrodynamic reactor insulated from the ambient medium (except for electromagnetic interaction) is based on nonstationary one-dimensional models.

Laser-Pulse Model. The shape and time and energy characteristics of a laser pulse determine the pattern of its interaction with a gasdisperse medium.

For computational investigations we used a model allowing a satisfactory reproduction of pulses realized on an experimental setup due to the variation in the parameters introduced into the model. The regularities of propagation of a laser pulse in the medium were described based on the model of exponential intensity damping, in which the quantities characterizing the absorption and scattering of radiation were determined by the local characteristics of a gasdisperse mixture.

The intensity of a laser pulse is represented in the form

$$I(t, x, y, z) = I_{max} f_1(t) f_2(x, y) f_3(z) .$$

The time variation in the pulse intensity is modeled by a continuous piecewise linear function constructed based on the characteristics of an actual laser system. The integral time characteristic of the laser pulse is found from the relation

$$\Theta = \int_0^\infty f_1(t)\, dt .$$

In the plane normal to the direction of propagation of the laser pulse, the spatial intensity distribution obeys the Gauss law:

$$f_2(x, y) = \exp\left[-2(x^2 + y^2)/H^2\right] .$$

The attenuation of the pulse in transmission by the medium is modeled using the Bouguer–Lambert–Beer law [9]:

$$f_3(z) = \exp(-\mu z) .$$

The absorption coefficient depends on the nature, state, and concentration of particles and on the wavelength of the transmitted light [2, 9].

The total energy of the laser pulse is related to its intensity and shape by the relation

$$Q = \int_0^{\infty} \int_0^{2\pi} \int_0^{\infty} I_{\max} f_1(t) \exp(-2r^2/H^2)\, r dr d\varphi dt .$$

After its integration, we obtain the formula

$$Q = \frac{\pi}{2} I_{\max} \Theta H^2 ,$$

from which we find the intensity of the initial pulse.

The above relations enable us to introduce specific characteristics of the laser pulse into the mathematical model and relate them to the parameters controlled in the experiment.

Laser-Heating Model. Not all the details of the dynamics of heating are of equivalent importance for determination of the threshold conditions of breakdown. Evaluation of radiation energy ensuring the beginning of developed evaporation of a particle and creating conditions for ionization of its vapor halo seems the most important [4].

It is assumed that, at a temperature lower than the melting temperature, we have only the warmup of a particle ($T_p < T_m$). When the melting temperature is attained, the particle is completely melted ($T_p = T_m$) and then it continues to be heated ($T_p > T_m$). The latent heat of the solid substance–liquid phase transition is not taken into account. Evaporation as an element of the physical process is triggered only from the instant of attainment of the boiling temperature ($T_p \ge T_v$). The evaporation rate is determined by the value of the energy absorbed by the particle. The radiation of other particles that is absorbed by the particle in question is disregarded. Convective heat exchange between the particle and the gas is not taken into account.

The model of heating, melting, and evaporation of a particle by laser radiation includes the equations of:

warmup of the particle to the melting temperature

$$c_p m_{p0} \frac{dT_p}{dt} = K_p I W_{p0} ; \tag{1}$$

melting of the particle

$$\Lambda_m m_{p0} \frac{d\zeta_p}{dt} = K_p I W_{p0} ; \tag{2}$$

warmup of the particle to the boiling temperature

$$c_p m_{p0} \frac{dT_p}{dt} = K_p I W_{p0} + \varepsilon\sigma (T^4 - T_p^4) S_{p0} ; \tag{3}$$

evaporation of the particle

$$\Lambda_v \frac{dm_p}{dt} = K_p I W_p + \varepsilon\sigma (T^4 - T_p^4) S_p . \tag{4}$$

The factor of efficiency of radiation absorption is evaluated by the complex refractive index of the medium [9].

Equations (1)–(4) are closed using relations allowing for the kinetics of the process of evaporation.

Model of Ionization of a Vapor Halo. The evaporated material of the particle forms a vapor halo around it; the vapor halo comes under the action of laser radiation and becomes ionized. For this range of parameters the basic mechanism of formation of a laser plasma is related to the pumping of radiation into the electron component due to the inverse braking effect and the subsequent formation of an electron avalanche. Other possible mechanisms of formation of the plasma, in particular, multiphoton ionization, are not governing. The processes of multiphoton ionization are pronounced in the visible and near-infrared spectral ranges [2, 3].

Assuming that all the parameters are uniformly distributed in the volume per particle, we give model relations for a quiescent medium; these relations describe the ionization of the vapor halo of a particle by laser radiation (in determining particle fluxes, it is assumed that the Boltzmann and Saha equations hold for them at the evaporation temperature, just as the condition of quasilinearity of the plasma):

the equation of heating of the particle's vapor halo due to the collisions of the electrons with the atoms

$$\frac{dT_a}{dt} = \frac{6m_e}{5m_a}(T_e - T_a)\,\alpha\nu\;; \tag{5}$$

the equation of heating of the electron component

$$\frac{dT_e}{dt} = -\left(T_e + \frac{2E}{5k}\right)\frac{1}{\alpha}\frac{d\alpha}{dt} - \frac{6m_e}{5m_a}(T_e - T_a)\,\nu + \frac{2}{5k}\frac{\mu I}{\alpha n}\;; \tag{6}$$

the equation of the kinetics of ionization of the particle vapor as a result of the electron impact

$$\frac{d\alpha}{dt} = \frac{A}{T_e^{9/2}}\,n\left[\alpha(1-\alpha)\frac{\beta^2 n}{1-\beta} - \alpha^3 n\right]; \tag{7}$$

the equation of change in the particle mass

$$\frac{dm_p}{dt} = -\frac{K_p I W_p}{\Lambda_v}\,. \tag{8}$$

Here $A = 1.05\cdot10^{-8}$ cm$^6\cdot$K$^{9/2}$. The equilibrium degree of ionization of the metal vapor is determined from the fact that the vapor leaving the particle surface is under the conditions satisfying the Saha equation at the evaporation temperature.

The closing equations necessary for integration of Eqs. (5)–(8) are prescribed by relations [10] and expressions enabling us to calculate the pressure and the concentration of heavy particles in the vapor halo.

In connection with the fact that the period of induction of a chemical reaction is comparable to the duration of a laser pulse, no considerable energy contribution from the chemical reaction is expected in the period of laser action. This enables us not to solve, as a first approximation, the energy equation for the gas component in the period of laser irradiation and to find the parameters of the mixture from a simplified model, assuming that we have adiabatic compression of the mixture by the halo vapor:

$$\left(\frac{p}{p_0}\right)\left(\frac{\Omega}{\Omega_0}\right)^{\gamma} = 1\,.$$

Assuming that the same pressure is established in the entire volume around the particle at each instant of time, we write the condition of constancy of the reaction-zone volume in the form

$$\left(\frac{p_0}{p}\right)^{1/\gamma} + \frac{m_v RT}{\Omega_0 p_0}\left(\frac{p_0}{p}\right) - 1 = 0\,. \tag{9}$$

Relation (9) is closing in the computational procedure and is resolved at each time step of numerical integration using the Newton method. When the pressure is known, the concentration of heavy particles is found from the equation of state.

Models of the Chemical Processes. In modeling the chemical kinetics in gas volumes having parameters nonuniformly distributed in space, we must take into account that integration of the equations of chemical kinetics requires that the time step be fairly small, since the computational formulas are used on relatively short time intervals when gasdynamic variables are restored.

Computational investigation of the kinetic processes is carried out within the framework of the model of a nonstationary ideal-mixing reactor. To model the chemical processes we use the induction-parameter model [11], which enables us to allow for the induction period of reaction during which the combustible mixture is in a stable state and chemical reactions in it never begin until the proper energy action is carried out.

Gasdynamic Processes in the Vapor Halo. Modeling of the gasdynamic processes in the particle's vapor halo is reduced to integration of the equations of nonstationary ideal-gas flow. We write the conservation laws in vector form:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}(\mathbf{U})}{\partial x} = \mathbf{G}(\mathbf{U}) . \tag{10}$$

The vector of gasdynamic variables, the flux vector, and the source term have the following form:

$$\mathbf{U} = \begin{pmatrix} \rho \\ \rho u \\ \rho e \\ \rho Y_l \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ (\rho e + p)\, u \\ \rho u Y_l \end{pmatrix}, \quad \mathbf{G} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \omega_l \end{pmatrix}.$$

The rate of change in the mass concentration of the component l of the mixture is determined in accordance with the Arrhenius law.

To discretize Eq. (10) we use the control-volume method and the idea of splitting by physical processes. The system of equations at the time step of integration is written in the following split form:

$$\mathbf{U}^{n+1/2} = \mathbf{U}^n - \left(\mathbf{F}^n_{j+1/2} - \mathbf{F}^n_{j-1/2}\right)\frac{\tau}{h} , \tag{11}$$

$$\mathbf{U}^{n+1} = \mathbf{U}^{n+1/2} + \int_{t_n}^{t_{n+1}} \mathbf{G}\, dt . \tag{12}$$

At the fractional step (11), the Godunov–Kolgan scheme [12] is used for calculation of the transposition of the quantities sought through the sides of the control volume. The computational fluxes are determined from the problem of disintegration of a discontinuity with the use of limiters to ensure monotony. The development of chemical processes in a system in which other processes are absent is considered at the fractional step (12). The source terms are found by solution of the microlevel problem. To ensure the stability of computations we use the internal step of numerical integration due to the rigidity of the microlevel problem.

Cumulative Coordinate of the Process. The state of the gasdisperse system is determined by the total value of the energy transmitted by the domain in question. The role of such a characteristic is played by the variable inheriting the dynamics of laser-pulse intensity [2]:

$$B(t, x, y, z) = \int_0^t I(t_1, x, y, z)\, dt_1 .$$

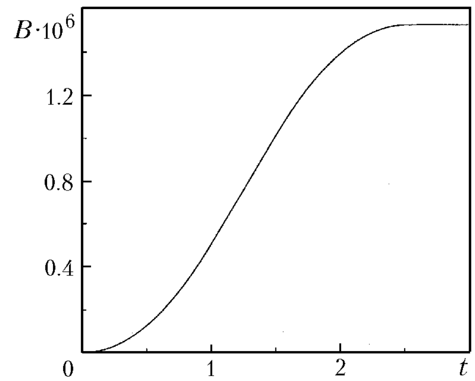

Fig. 1. Relation of the cumulative coordinate of the process to the time from the beginning of the action of a laser pulse. B, J/cm^2; t, μsec.

The relation of the cumulative characteristic to the time from the beginning of the action of a laser pulse is shown in Fig. 1 at t_i = 2.6 μsec and I_{max} = 2.1·10^6 W/cm^2.

In processing the results of numerical modeling that correspond to the microlevel problem, it has been established that various realizations of the process of breakdown, which differ in pulse duration and shape and in position of a particle relative to the beam axis, exert no influence on the value of the cumulative energy characteristic of the breakdown [5]. This characteristic is universal and may be used for comparison of the data obtained under various conditions.

We take the value of the cumulative characteristic, counted off from the beginning of the process of evaporation of a particle (it is precisely the appearance of the vapor component that triggers the mechanism of formation of an optical plasma) as the independent coordinate. When the new coordinate is used, the characteristics of evaporation of the particle and of dynamics of laser breakdown appear identical in practice [5]. A small stratification of the curves is observed only for the electron and ion temperatures; however, in this case, too, the above dependence may be considered to be universal for engineering purposes.

We consider the following values, respectively, as the characteristic values of the cumulative variable: B_1 for the beginning of the process of vaporization, B_2 for the end of the process of vaporization and the beginning of the process of ionization of the particle's vapor halo, and B_3 for the beginning of laser breakdown.

In new variables, the universal dependences describing the process of interaction of laser radiation with the particle have the following form:

the equation for the particle mass is

$$\frac{m_p}{m_{p0}} = \begin{cases} 1\,, & B < B_1\,; \\ \dfrac{B - B_1}{B_2 - B_1}\,, & B_1 < B < B_2\,; \\ 0 & B > B_2\,; \end{cases} \tag{13}$$

the equation for the degree of ionization is

$$\alpha = \begin{cases} 0\,, & B < B_3\,; \\ 1\,, & B > B_3\,; \end{cases} \tag{14}$$

the equation for the temperature of heavy particles is

$$T = \begin{cases} 0\,, & B < B_3\,; \\ C\,\sqrt{B - B_3}\,, & B > B_3\,. \end{cases} \tag{15}$$

The characteristic values of the cumulative coordinate, established based on numerical calculations, are as follows: B_1 = 0.56·10^6 J/cm^2, $B_2 - B_1$ = 0.54·10^6 J/cm^2, $B_3 - B_1$ = 0.72·10^6 J/cm^2, and C = 50.0 K·cm/J$^{1/2}$. These values have been calculated for a specific system; therefore, they have differing characteristics for particles of another shape and material.

Method of Calculation of the Characteristics of a Probing Beam. The transmission of a laser beam by the gasdisperse medium is accompanied by its absorption and scattering on dispersed inclusions. In development of the processes of evaporation and plasma formation on particles, the absorption and scattering of laser radiation are intensified, which leads to a further reduction in the depth of penetration of the beam into the system. Accurate determination of the coefficients of absorption and scattering represents a fairly difficult problem requiring that the problem of interaction of the electromagnetic wave with microplasma formations be solved. At the same time, based on the approximate models using the universal dependences (13)–(15), we can evaluate the processes accompanying the penetration of the beam into the system.

Into the spatial domain $[0, X_1] \times [0, X_2]$ we introduce a computational grid $x_j = jh_1$ $(j = 0, ..., N_1)$, $r_k = kh_2$ $(k = 0, ..., N_2)$, which subdivides the system into finite volumes. We consider the sequence of time states $t_n = n\tau$ $(n = 0, ..., N_3)$. The grid steps and the time step are found from the following relations:

$$h_1 = \frac{X_1}{N_1 - 1} , \quad h_2 = \frac{X_2}{N_2 - 1} , \quad h_3 = \frac{t_{\rm i}}{N_3 - 1} .$$

Let us assume that the values of the universal cumulative coordinate of the process B_{jk}^n are known for all the control volumes of the computational domain at the instant of time t_n. The problem lies in calculating the new state of the system, which is characterized by the value of the cumulative coordinate B_{jk}^{n+1}, and finding the characteristics of the energy contribution as functions of the value obtained.

The values of the running radiation intensity for each vertical layer of control volumes are known from the calculation of the previous cross section. We assume that this is the input intensity for the control volume in question. The processes of absorption in the control volume are evaluated by the effective area of shading of the beam by the dispersed inclusions. In evaporation of a particle, its effective cross section is determined as the cross section of an extending vapor halo. It is assumed that all the particles in this control volume act identically; therefore, each control volume requires that the dynamics of only one representative particle be controlled.

To determine the intensity of the beam leaving the control volume at the instant of time t_{n+1} we have the dependence

$$I_2^{n+1} = I_1^{n+1} \left(1 - n_{\rm p} W_{\rm p} h_1\right) .$$

The calculations show that for the prescribed radiation parameters the processes of evaporation occur with a high intensity and the gas flows off the particle surface with the velocity of sound. For a lamellar particle, the vapor volume at the instant of time t is evaluated by the formula

$$\Omega_{\rm v} = a \left(t - t_{\rm v}\right) W_{\rm p0} .$$

The effective cross section of a vapor formation is found from the relation

$$W_{\rm p} = W_{\rm p0} + \left(\frac{9\pi}{16} \Omega_{\rm v}^2\right)^{1/3} .$$

These formulas and the universal dependences (13)–(15) enable us to determine the parameters of the system in this vertical layer of control volumes, whereas the successive calculation of horizontal layers carried out makes it possible to determine the new state of the system.

Calculation Results. The calculations were carried out for the following parameters: $Q = 0.5$–5 J, $t_{\rm i} = 2$–8 μsec, $\lambda = 4.2$ μm, $H = 1$–3 cm, $\Theta = 1.5$ μsec, and $\kappa_{\rm p} = 0.5$–5 g/m^3. The dispersed inclusions are aluminum particles having a lamellar shape; they are considered as $5 \times 5 \times 50$ μm plates. The thermal and optical properties of a particle have been taken from reference books with allowance for their dependence on temperature.

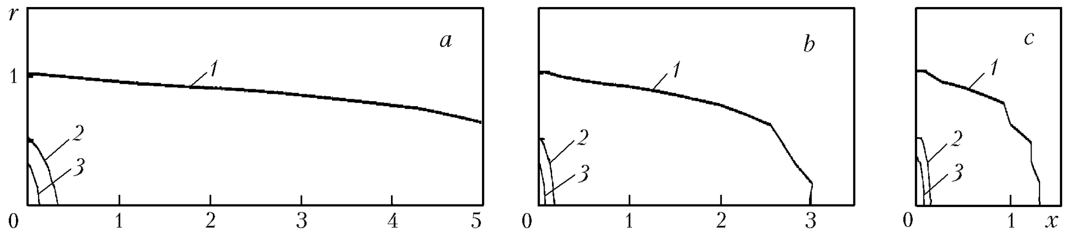

Fig. 2. Position of the front of melting (1), evaporation (2), and plasma formation at the end of the laser pulse (3) for different values of the mass concentration of the impurity: a) κ_p = 0.25, b) 0.5, and c) 1.0 g/m^3. *r*, cm; *x*, m.

The boundaries of the zone of propagation of the front of melting and evaporation of dispersed inclusions and of the plasma-formation front have been taken as the characteristic of interaction of the beam with the gasdisperse system for visual representation. The position of these boundaries changes with time and is given for the instant of completion of the pulse and cessation of the energy contribution to the medium.

The influence of the mass concentration of particles on the characteristics of penetration of the beam into the system is shown in Fig. 2 (t_i = 2.6 μsec, Q = 1.5 J, and H = 1.5 cm). A decrease in the concentration of the impurity contributes to a considerable increase in the penetration depth of the front of both melting and evaporation and of the plasma-formation front (Fig. 2a). An increase in the concentration of particles causes shielding effects (wavy boundary of the melting or evaporation front) to appear. The penetration depth of the front of melting of particles is substantially reduced, whereas the position of the evaporation and plasma-formation fronts remains constant in practice (Fig. 2b and c).

Only the warmup and evaporation of particles are observed for a concentration of the metallized inclusions of 0.5 g/m^3 and a pulse energy of 1 J. The penetration depth of the melting front is about 2 m and has the form of a narrow cylindrical formation about 1 cm in diameter. With increase in the pulse energy to 2 J, a zone in which a laser plasma is formed appears. This zone has a length of about 0.25 m for a length of the developed-evaporation zone of approximately 0.5 m. Noteworthy is the appearance of nonmonotony on the front of this zone, which is attributed to the shielding action of microplasma formations. Further increase in the pulse energy contributes only to the development of the plasma zone and does not lead to a rearrangement and noticeable increase in the penetration depth of the evaporation zone. It might be expected that a limit of the penetration depth of the evaporation front exists for this concentration.

Focusing of the beam is of considerable importance for the characteristics of energy contribution, which is quite obvious, since the Gauss radius of the beam determines the level of intensity influencing the value of the cumulative coordinate.

The results obtained open up possibilities for further improvement of the system of mathematical modeling of the processes occurring in laser breakdown in gasdisperse systems and for realization of the parametric optimization of the systems based on phenomena of similar nature. In particular, it becomes appropriate to seek the values of the concentration and the laser-pulse energy that ensure the most efficient characteristics of interaction of the beam with the gasdisperse system.

CONCLUSIONS

1. We have constructed mathematical models of the elementary stages of the process, among which are the warmup of the condensed fraction, the evaporation of a particle, the formation of a vapor halo, the appearance of free electrons due to the thermal ionization on the shock-wave front, and the development of an electron avalanche as well as the development of the processes of chemical reaction and gasdynamic processes in the region of a condensed particle.

2. We have given the results of numerical modeling of the dynamics of the process based on successive solution of the problems describing its stages. Generalized dependences allowing prediction of the characteristics of laser breakdown on condensed inclusions and optimization of the parameters of the initiating laser pulse have been constructed. The characteristics of the region of efficient supply of energy to the system have been determined.

3. We have singled out the directions in further development of a software system, in particular, the development of modeling aids for the processes of nonequilibrium evaporation of particles, which seem important for description of the initial stage of laser breakdown on metal particles and the dynamics of a vapor halo.

NOTATION

a, velocity of sound, m/sec; *A*, proportionality factor, $m^6 \cdot K^{9/2}$; *B*, cumulative coordinate of the process, J/m^2; *c*, heat capacity, J/(kg·K); *C*, proportionality factor, $K \cdot m/J^{1/2}$; *e*, total energy of unit mass, J/kg; *E*, activation energy, J; f_1, function describing the variation in the pulse intensity with time; f_2, function describing the spatial distribution of the pulse intensity; f_3, function describing the attenuation of a pulse in transmission by the medium; **F**, flux vector; *h*, spatial step of discretization, m; *H*, characteristic width of the focusing zone, m; **G**, source term; *I*, laser-pulse intensity, W/m^2; *k*, Boltzmann constant, J/K; *K*, factor of efficiency of radiation absorption; *m*, mass, kg; *n*, number concentration, $1/m^3$; *N*, number of grid nodes; *p*, pressure, Pa; *Q*, total laser-pulse energy, J; *r*, radial coordinate, m; *R*, universal gas constant, J/(kg·K); *S*, area, m^2; *t*, time, sec; *T*, temperature, K; *x*, *y*, *z*, spatial coordinates, m; *X*, dimension of the computational domain, m; *Y*, mass concentration of the component of the mixture; *u*, velocity, m/sec; **U**, vector of the unknowns; *W*, area of the effective cross section, m^2; α, degree of ionization; β, equilibrium degree of ionization; γ, adiabatic exponent; ε, emissivity factor of the particle surface; ζ, relative fraction of the melt; Θ, integral time characteristic of a laser pulse, sec; κ, mass concentration of the impurity, kg/m^3; λ, wavelength, m; Λ, specific heat of phase transition, J/kg; μ, coefficient of absorption of radiation, 1/m; ν, frequency of collisions of electrons with atoms and ions, 1/sec; ρ, density, kg/m^3; σ, Stefan–Boltzmann constant, $W/(m^2 \cdot K^4)$; τ, time step of integration, sec; φ, polar angle; ω, chemical-reaction rate, 1/sec; Ω, volume, m^3. Subscripts and superscripts: a, atom; e, electron; i, laser pulse (impulse); *j* and *k*, control volume of the difference grid; *l*, component of the mixture; max, maximum; *n*, time step; p, particle; v, evaporation; 0, initial instant of time; *, threshold value of the parameter.

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