

THEORY OF PLASMA DYNAMICS IN THE CASE OF SOLID MATTER SURFACE DESTRUCTION BY PULSES OF POWER RADIATION

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We present a theoretical interpretation of the destructive effect of a powerful pulse of radiation on a substance surface. We study the specific features of both the dynamics of the surface destruction of a material and the spatio-temporal dynamics of a gas phase. This phase arises due to local phase transitions under the rapid heating of the surface by a laser pulse, which induces the formation (the burn-out) of a corrosion crater. The differential equation which describes the burning dynamics of a plasma torch is formulated. The general solution of the equations of the dynamics of a plasma-gaseous phase is obtained, and its "behavior" is analyzed for different levels of the interaction of radiation with gas.

1. Introduction

The creation of lasers at the beginning of the 1960s defined the top position of superpowerful laser systems in the investigations of a high-temperature plasma and the matter behaviour under extreme conditions. By means of short pulses, it became possible to investigate the dynamics of the fast processes which occur in atoms, molecules, and solids. Laser radiation (laser doping, annealing, thermal treatment, plating, etc.) is used for the material treatment (the surface modification) in many up-to-date technologies.

The possibility of a local influence on small surfaces, the high-speed heating, and the manoeuvrability in the control over a laser beam make the laser-based methods of modification of materials more and more attractive.

New generations of lasers and laser systems can generate femtosecond pulses. Femtosecond laser systems

with a light pulse duration of 10–1000 fs allow one to obtain, by focusing, the enormous light intensity in the range 10^{14} – 10^{21} W/cm² [1, 4]. After falling on a solid matter surface, such high-intensity pulses can lead, under some conditions, to considerable damages of this surface and are of special interest [1–7]. The examples of such a treatment are shown in Figs. 1 and 2.

As one can see, the damages made by laser pulses are different in their forms. Of importance is the fact that the surface destruction can be accompanied by fusing of the crater edges or occur without it (the latter may be useful, e.g., in medicine). The results of these experiments indicate that the fusing of the crater edges depends essentially on the length and intensity of the light pulse which falls to the surface.

A lot of experimental and theoretical investigations are closely related to the problem of the destruction of solid matter surfaces by short high-power laser pulses. Recently, these investigations have moved to the domain of very short pulses [1–7]. In this connection, there arises the necessity to study the processes that run during the interaction of very short laser pulses with plasma. In turn, the plasma formation depends significantly on the structure and properties of the surface layer of a target.

The "behaviour" of a condensed matter under influence of a power laser pulse is ambiguous. In spite of a large number of experimental works in this area, the physics of processes that happen under irradiation of



Fig. 1. 100-micron craters made in steel by a nanosecond pulse (left) and a femtosecond pulse (right) [1]

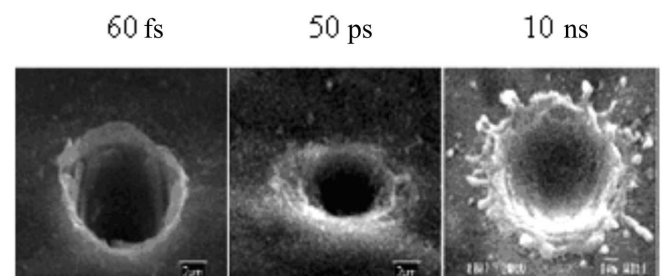


Fig. 2. Scanning electronic microscopic images of the craters produced by 60-fs, 50-ps, and 10-ns pulses on aluminum samples at $2.7 \mu\text{J}/\text{pulse}$ [2]

matter is clarified incompletely [1]. Very often, the theoretical models used for the interpretation of these processes are based on the assumption that, during the whole process of laser treatment, the phase state of an investigated object does not change, and the possibility of fast qualitative changes is ignored. In our opinion, the consideration of such changes, i.e. local phase transformations, is essential and must underlie the processes under investigation.

In other words, the development of the theory of the interaction of intense pulse energy flows with a matter surface which would take local phase transformations during the surface destruction into account is, may be, the most consecutive approach.

According to experimental estimations [8], the characteristic level of energy, from which the active destruction of the surface begins practically without the formation of a liquid phase, exceeds $10^7 \div 10^8$ W/cm², depending on a material. If the energy flow is substantially higher than this value, its considerable part is spent on the direct solid-gas phase transition. A liquid phase is practically absent in the area of treatment in this case.

Such flows represent the main interest for this work. In order to define the boundary which separates a treatment with the formation of the liquid state and a treatment which is not accompanied by the surface melting, we will consider the superficial layer of the matter on an area with the size equal to the cross-section of a laser pulse. To prevent the appearance of a liquid phase on the solid surface, its temperature during the pulse action has to amount, at least, to the critical value T_c , without going out the borders of the phase surface of state of the matter which corresponds exceptionally to the solid phase. In this case, the pressure in this near-surface area of the solid phase must also exceed some critical value P_c . Because a laser pulse is considered, the necessary condition, under which the system gets in the mentioned area is

$$P_c < q_s(1 + R)/c,$$

where q_s is the power of an electromagnetic wave falling on the matter surface, R is the light reflectivity, and c is the light speed.

Taking into account that the equation of state $PV = \nu R_g T_c$ holds on the critical isotherm of the gas phase at an arbitrary pressure P in a volume V , where R_g is gas constant and ν is the number of moles of a gas, it is possible to estimate the pressure P_c which provides the implementation of the above condition. This value can be estimated from the next consideration.

In order that the liquid phase does not appear, the solid phase after the phase transition must fall on an isotherm which coincides with or lies above the critical isotherm at the temperature T_c . Examining just the critical isotherm, we will get the sought threshold value of P_c , for which the equation of state for a gas takes the form $P_c V_c = \nu R_g T_c$. In this equation, the volume V_c remains indefinite so far. For its estimation, it is possible to take advantage of fact that, at the moment of the phase state transition from solid to gas, the change of the volume $V^{\text{sol}} \rightarrow V$ is not so substantial comparing to a similar change for other points of isotherm T_c (where this change is large). That is why the volume V_c can be considered to be practically equal to the corresponding volume of the solid phase V_c^{sol} . Since the volume of one mole of a solid V_μ is determined by the ratio $V_\mu = \mu/\rho^{\text{sol}}$, where μ is the molecular mass and ρ^{sol} is the density, the volume of ν moles is obviously equal to $V_c^{\text{sol}} = \nu\mu/\rho^{\text{sol}}$. Substituting this value of the volume in the equation of state $P_c V_c = \nu R_g T_c$ for V_c , we get the estimation $P_c = R_g T_c \rho^{\text{sol}}/\mu$. In this case, the sufficient condition for a flow q_s looks like

$$q_s > \frac{R_g T_c \rho^{\text{sol}} c}{\mu} \frac{1}{1 + R}.$$

In practice, such an estimation is interesting for the initial flow q_{in} which is related to the flow q_s which passed in a solid by the relation $q_s = (1 - R) q_{\text{in}}$. Then, for the initial value of the flow, we get

$$q_{\text{in}} > \frac{R_g T_c \rho^{\text{sol}} c}{\mu} \frac{1}{1 - R^2}.$$

By this formula, we made some estimations for specific materials. They show that, for example, the superficial value of a stream must meet the condition $q_{\text{in}} > 6 \times 10^7 \times \frac{1}{1 - R^2} \sim 2 \times 10^8$ for aluminum, $q_{\text{in}} > 4 \times 10^7 \times \frac{1}{1 - R^2}$ for copper, $q_{\text{in}} > 6 \times 10^7 \times \frac{1}{1 - R^2}$ for tungsten, $q_{\text{in}} > 4 \cdot 10^7 \times \frac{1}{1 - R^2}$ for chrome, and $q_{\text{in}} > 3 \times 10^7 \times \frac{1}{1 - R^2}$ for titanium. As seen, such estimations do not contradict the experimental information [8]. Hence, we will name flows intensive, if they meet the condition got earlier.

Here, the problem of the destruction of a solid surface under the action of flows with just such intensities is considered. In this case, the irradiated solid surface is evaporating without melting. In the following section, we consider a mathematical model of the processes running during a destructive treatment.

2. Formulation of the Dynamics of the Gas Phase

Under certain conditions as for the light intensity and the pulse duration, the destruction of the substance by power laser pulses occurs by means of a spontaneous phase transformation of the solid surface of this substance into the gas phase considered by us as a continuous gaseous medium. The system of equations describing the dynamics of this phase is as follows:

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \mathbf{v}) = R_m, \quad (1)$$

$$\frac{d\mathbf{v}}{dt} + \frac{1}{\rho} \operatorname{grad} P = \mathbf{f}, \quad (2)$$

$$\rho \frac{dU}{dt} + P \operatorname{div} \mathbf{v} + \operatorname{div} \mathbf{Q} = 0. \quad (3)$$

Here, U , ρ , \mathbf{v} are, respectively, the intrinsic energy of the continuous medium per unit mass, the density of this medium, and the convection velocity vector, \mathbf{Q} is the generalized energy flow in the medium, and P is the pressure exerting on the system. System (1)–(3) is essentially inhomogeneous. The reason for this is the appearance of microclusters and microdrops in the gas phase of sources-outflows, which can be taken into account by introducing the bulk mass sources and sinks R_m [9] into Eq. (1) and the mass force density \mathbf{f} into Eq. (2) accounting the radiation action on the gas-like matter flow [10]. The function R_m and force \mathbf{f} are defined by the specific statement of the problem. In particular, they can entirely or partially be defined by the condition of the compatibility of the whole system (1)–(3). Obviously, system (1)–(3) must be completed by boundary conditions on the interface of the solid and the gas [11]:

the mass flow balance condition responsible for the configuration of a crater formed during the surface destruction

$$\rho_s (\mathbf{v}_s \times \mathbf{n}) - \rho_s^{\text{sol}} (\mathbf{v}_s^{\text{sol}} \times \mathbf{n}) = 0; \quad (4)$$

the pulse flow balance condition defining the corrosive torch form (the gas phase) arising during the surface destruction

$$P_s n_i + \frac{1}{c} (\mathbf{n} \times \mathbf{q}_s) + \rho_s (\mathbf{n} \times \mathbf{v}_s) \left(v_s^i - (v_s^{\text{sol}})^i \right) + (P_{ij}^{\text{sol}})_s n_j = 0; \quad (5)$$

and the condition of energy flow balance

$$(\mathbf{n} \times \mathbf{v}_s) \left(\rho_s H_s + \rho_s \frac{v_s^2}{2} \right) + L_0 (\mathbf{n} \times \mathbf{q}_s) -$$

$$-L\lambda_s (\mathbf{n} \times \operatorname{grad} T)_s - (\mathbf{n} \times \mathbf{v}_s) \rho_s U_s^{\text{sol}} = 0. \quad (6)$$

Here, H_s is a heat Gibbs function (enthalpy) describing the state of a macroscopic system in a thermodynamic equilibrium, when entropy and pressure are the main independent variables; v_s^i , $(v_s^{\text{sol}})^i$ are, respectively, the components of the speed vectors of the gaseous and condensed media on the interface, U_s^{sol} is the intrinsic energy of the condensed medium per unit mass; $(P_{ij}^{\text{sol}})_s$ is the surface value of the stress tensor, and L and L_0 are, respectively, the light and thermal loss factors for the transition from the gas to the solid. The index “ s ” is for the value of a quantity on the interface. The size of this interface is substantially smaller than the wavelength (4000 Å).

Conditions (5) and (6) for the given problem were made more precise in [12] with regard for the influence of the radiation flow on a material of the surface.

The third equation of system (1)–(3) depends on the intrinsic energy per unit mass of the condensed continuous medium U . Since the gas is practically ideal (low density and high temperature), we will use the formula for the ideal gas energy $U \equiv P/(\gamma\rho)$, where $\gamma = \kappa - 1$, and κ is the polytrope exponent. With such a definition of intrinsic energy, Eq. (3) becomes

$$\frac{dP}{dt} + \mathbf{v} \operatorname{grad} P + \kappa P \operatorname{div} \mathbf{v} + \gamma \operatorname{div} \mathbf{Q} = \frac{PR}{\rho}, \quad (7)$$

where $\partial\rho/\partial t$ is taken from Eq. (1).

We will solve system (1), (2), (7) in the barotropic approximation, by assuming that the density and the velocity depend on the pressure: $\rho \equiv \rho(P)$ and $\mathbf{v} \equiv \mathbf{v}(P)$. Using these relations in system (1), (2), (7), we get

$$\begin{cases} P_t + \left(\mathbf{v} + \frac{\rho}{\rho'} \mathbf{v}' \right) \operatorname{grad} P = \frac{R}{\rho'}, \\ P_t + \left(\mathbf{v} + \frac{\mathbf{v}}{(\mathbf{v} \times \mathbf{v}') \rho} \right) \operatorname{grad} P = \frac{(\mathbf{v} \times \mathbf{f})}{(\mathbf{v} \times \mathbf{v}')}, \\ P_t + (\mathbf{v} + \kappa P \mathbf{v}') \operatorname{grad} P = \frac{PR}{\rho} - \gamma \operatorname{div} \mathbf{Q}, \end{cases} \quad (8)$$

where $\mathbf{v}' \equiv d\mathbf{v}/dP$ and $P_t \equiv \partial P/\partial t$.

The compatibility condition for Eqs. (1) and (3) yields

$$\rho = aP^\eta, \quad R = -\frac{a \operatorname{div} \mathbf{Q}}{P^{2\sigma}}, \quad (9)$$

where a is the integration constant, $\eta \equiv 1/\kappa$, and $\sigma \equiv (\kappa - 1)/(2\kappa)$. Further, taking account of (9) in (8)

and the compatibility of both remaining equations, we obtain

$$\kappa a P^{2\beta} \mathbf{v}'(\mathbf{v} \times \mathbf{v}') = \mathbf{v}, \quad \mathbf{f} = -\kappa \mathbf{v}' \operatorname{div} \mathbf{Q}, \quad (10)$$

where $\beta \equiv (\kappa + 1)/(2\kappa)$.

Three boundary conditions (4)–(6) are formulated for the local coordinate system connected with the moving surface. Therefore, we represent the velocity in the same system as

$$\mathbf{v} = \mathbf{e}_l \cos(\gamma)v + \mathbf{e}_f \cos(\beta)v + \mathbf{e}_n \cos(\alpha)v, \quad (11)$$

where \mathbf{e}_l , \mathbf{e}_f , \mathbf{e}_n are the local coordinate system orthonormal basis vectors, \mathbf{e}_n coincides with the normal to the solid-gas interface, the basis vectors \mathbf{e}_l , \mathbf{e}_f are perpendicular to the normal and are tangent to the interface, and $\cos(\alpha)$, $\cos(\beta)$, $\cos(\gamma)$ are the direction cosines of the projection angles on the system's basis vectors.

The momentum balance condition (5) for components and the condition for the direction cosines $\cos^2(\alpha) + \cos^2(\beta) + \cos^2(\gamma) = 1$ were used for the determination of $\cos(\alpha)$, $\cos(\beta)$, and $\cos(\gamma)$ near the surface. From this, it follows that $\cos(\gamma) \sim 0$, $\cos(\beta) \sim 0$, $\cos(\alpha) = \pm 1$. Taking into account that the gas velocity vector is oppositely directed to the surface normal, we have, in the chosen geometry, $\cos(\alpha) = -1$, or $\alpha = \pi$. In other words, the solutions to (10) are as follows:

$$\mathbf{v}_s \equiv -v \mathbf{e}_n \quad v_s = -\frac{P_s^\sigma}{\sigma \sqrt{\kappa a}}. \quad (12)$$

The constant of integration in the velocity definition is supposed to be zero because the gas velocity is zero at $P = 0$, when there are no external pressure and conditions for the surface destruction and the crater formation.

If we take into account (12), system (8) is reduced to one equation

$$P_t - \frac{\alpha}{\gamma} \sqrt{\frac{\kappa}{a}} P^\sigma (\mathbf{e}_n \times \operatorname{grad} P) = -\kappa \operatorname{div} \mathbf{Q} \vartheta(\tau - t). \quad (13)$$

Based on the fact that the energy influence has pulse nature, we introduce the factor $\vartheta(\tau - t)$ in Eq. (13) for the flow \mathbf{Q} , where τ is the effective pulse length, and $\vartheta(\tau - t)$ is the Heaviside step function. It is equal to unity at $t \leq \tau$ and to zero when $t > \tau$. This factor will limit the light-gas interaction time.

Since the main accent of this paper consists in the description of the kinetic characteristics of the gas near the surface, the boundary condition (6) takes on a special significance as the equation describing the

processes under study. But, as one can see, this boundary condition involves the temperature as a variable which can be determined from the equation of state in terms of pressure and density as

$$P = \frac{\rho k_B T}{m_a}, \quad (14)$$

where m_a is the mass of an atom of the evaporated substance, and k_B is the Boltzmann constant.

The thermal conductivity of the gas is a function of temperature and can be presented as

$$\lambda_s = \frac{2R_g \sqrt{m_a k_B}}{3\pi \sqrt{\pi} \gamma \mu_a d_a^2} \sqrt{T_s}, \quad (15)$$

where R_g is the gas constant; μ_a is the gas molecular weight; and d_a is the effective diameter of a molecule.

Using definition (14), we represent the thermal capacity λ_s as a function of only the pressure and density of the ambient medium. Taking into account (14) and (15), the boundary condition (6) can be formulated as

$$b \frac{\gamma P_s^{\sigma-\eta} L}{\kappa a^{3/2}} (\mathbf{e}_n \times \operatorname{grad} P)_s - a P_s^\eta (\mathbf{e}_n \times \mathbf{v}_s) \times \left[\frac{\kappa P_s^{2\sigma}}{\gamma a} + \frac{v_s^2}{2} + \varphi_s^{\text{sol}} \right] - L_0 (\mathbf{e}_n \times \mathbf{q}_s) \vartheta_\tau = 0. \quad (16)$$

Here, $b \equiv 2R_g m_a^2 / (3\pi \sqrt{\pi} \gamma \mu_a d_a^2 k_B)$, φ_s^{sol} — specific heat of the condensate-gas phase transformation. The binding energy U_s^{sol} of the system is determined by the particle interaction and is negative by definition. Therefore, we take the relation $U_s^{\text{sol}} = -\varphi_s^{\text{sol}}$ into account in (16). Here, as in Eq. (13), the duration of the interaction of an energy pulse with the gas is limited by the function $\vartheta(\tau - t) \equiv \vartheta_\tau$.

To reduce the boundary condition (16) to the form, when it depends only on the near-surface pressure P_s and does not depend on the space derivatives conditioned by the factor $(\mathbf{e}_n \times \operatorname{grad} P)_s$, we determine this factor from the boundary condition (16) and insert it in Eq. (13) projected onto the substance surface. As a result, the boundary condition takes the form

$$\frac{dP_s}{dt} = -\frac{2a^{3/2} \kappa^2 \alpha \varphi_s^{\text{sol}}}{\gamma^3 b L} P_s^{2\eta+\sigma} - \frac{2\sqrt{a} \kappa^3 \alpha^2}{\gamma^5 b L} P_s^{2\beta+\sigma} + \vartheta_\tau \frac{e_q}{N} \frac{a \alpha \kappa^{3/2} q_{\text{in}} L_0}{\gamma^2 b L} P_s^\eta + \vartheta_\tau e_q \kappa a^{3/2} q_{\text{in}} P_s^{\eta+\beta} h(\omega), \quad (17)$$

where the factor $1/N \equiv (\sqrt{1 + (\partial S/\partial x)^2 + (\partial S/\partial y)^2})^{-1}$ appears from the definition of a normal to the surface,

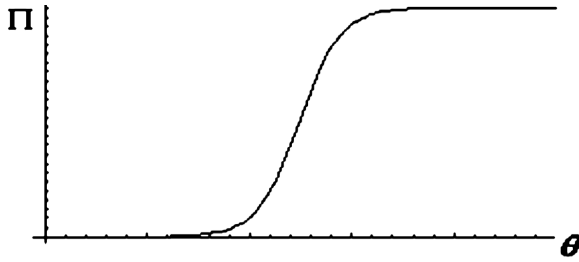


Fig. 3. Diagrammatic dependence $\Pi(\theta)$ during a pulse

in which the function S determines the crater surface form. In the laboratory frame which is fixed relative to the solid phase, a light flow spreads along the z axis, i.e. $\mathbf{Q} = e_z Q$. As a result, $\text{div } \mathbf{Q}$ depends only on z on the surface: $(\partial Q / \partial z)_s \equiv (Q_z)_s$. By the Bouguer–Lambert–Beer law, we have $Q_z = -k q$, where $k = \rho \sqrt{\rho P} h(\omega)$ is the electromagnetic radiation absorption factor [13], while $h(\omega)$ is the constant part of the absorption factor which does not depend on pressure. Consequently, $(Q_z)_s = -k q_s$. The factor $e_q \equiv q_s / q_{in}$ determines the radiation power loss and can be represented generally as a product of some amplitude function $f(x, y)$ and the exponentially decaying factor which depends on the absorption coefficient and the function S : $e_q \equiv f(x, y) \exp(-k S(x, y))$.

We reduce Eq. (17) to the dimensionless form using the substitutions $P \equiv P_0 \Pi$, $t \equiv t_0 \theta$, $S \equiv S_0 \Sigma$, $x \equiv S_0 X$, $y \equiv S_0 Y$:

$$\frac{\partial \Pi}{\partial \theta} = (-1 + \Lambda e_q \vartheta_\tau) \Pi^{\beta+\eta} - \Pi^{\beta+1} + \frac{1}{N} e_q \vartheta_\tau \Pi^\eta. \quad (18)$$

Here,

$$a = \frac{\kappa \alpha}{\varphi_s^{\text{sol}} \gamma} P_0^{2\sigma}, \quad t_0 = \frac{b \gamma^4 \varphi_s^{\text{sol}} L}{q_{in} \alpha^2 \kappa^{5/2} L_0},$$

$$P_0 = \frac{b \gamma^6 L \sqrt{\varphi_s^{\text{sol}}}}{2 \alpha^{5/2} \kappa^{7/2} t_0},$$

$$\Lambda = \frac{b L \gamma^3 q_{in}}{2 \kappa \alpha \varphi_s^{\text{sol}}} h(\omega), \quad S_0 = \frac{2 b \gamma^2 (\varphi_s^{\text{sol}})^{3/2} L}{q_{in} \alpha^{3/2} \kappa^{1/2} L_0}. \quad (19)$$

Equation (18) is a nonlinear partial differential equation. In addition to the power function of the pressure, the nonlinearity of the equation is conditioned also by the parameter e_q , which can be written in the dimensionless form with regard for (19) as

$$e_q = f(x, y) \exp(-\Lambda \Pi^{\eta+\beta} \Sigma). \quad (20)$$

The presence of a partial derivative with respect to θ is caused by that Eq. (18) depends on spatial variables parametrically because of the factors $1/N$ and e_q .

3. Some Analytical Solutions and Their Discussion

The powers of the pressure Π in (18) and (20) are not integers and depend on the polytrope parameter κ which essentially differs from the ideal value due to the presence of microclusters and microdrops. In this sense, we consider the limiting case $\kappa \rightarrow 1$ [14].

As one can see from Eq. (20), the dependence of e_q on Λ, Π , and Σ is enough complicated. Moreover, the normal N depends on Σ too, which, like e_q , enters Eq. (18). All this makes the analysis of this equation to be very complicated. Therefore, we consider, as a particular case, the process which can be described by Eq. (18) under some assumptions. First of all, we consider the situation where the incident beam width is much more than the crater depth. This allows us to neglect the coordinate dependence of a crater form Σ at least far from the crater edges. Moreover, the quantity $1/N$ will be absent in the equation for pressure. In this case, due to the absence of a transverse pulse structure, the parameter e_q loses the dependence on the amplitude function $f(x, y)$ (it is equal to unity) and can be determined for $\kappa \rightarrow 1$ it as $\bar{e}_q = \exp(-\Lambda \bar{\Pi}^2 \bar{\Sigma})$, where $\bar{e}_q, \bar{\Pi}$, and $\bar{\Sigma}$ are the average values of the corresponding functions. In other words, for $\kappa \rightarrow 1$, Eq. (18) can be approximately written as

$$\frac{d\Pi}{d\theta} = (-1 + \Lambda \bar{e}_q \vartheta_\tau) \Pi^2 - \Pi^2 + \bar{e}_q \vartheta_\tau \Pi. \quad (21)$$

Due to the properties of the Heaviside function, Eq. (21) breaks out into two separate equations, each of them is responsible for a part of the process depending on time:

- 1) $d\Pi_1/d\theta = ((-2 + \Lambda \bar{e}_q) \Pi_1 + \bar{e}_q) \Pi_1$ with the initial condition $\Pi_1(0) = \Pi_{in}$,
- 2) $d\Pi_2/d\theta = -2\Pi_2^2$, at $\theta \geq \theta_\tau$.

Correspondingly, we have two solutions in the case $\bar{e}_q = \text{const}$:

$$\Pi_1 = \bar{e}_q (C_1 \exp(-\bar{e}_q \theta) - \Lambda \bar{e}_q + 2)^{-1},$$

$$\Pi_2 = [2(\theta + C_2)]^{-1}. \quad (22)$$

Here, C_1 and C_2 are the integration constants. The constant C_1 is defined by the condition $\Pi_1(0) = \Pi_{in}$, from which $C_1 = \bar{e}_q \Pi_{in}^{-1} - 2 + \Lambda \bar{e}_q$ follows. Then we get

$$\Pi_1(\theta) = ((\Pi_{in}^{-1} - 2\bar{e}_q^{-1} + \Lambda) \times$$

$$\times \exp(-\bar{e}_q \theta) - \Lambda + 2\bar{e}_q^{-1})^{-1}. \quad (23)$$

The obtained function $\Pi_1(\theta)$ (23) describes the process corresponding to the active ejection of the solid substance into the gas phase until the action of a pulse falling onto the surface stops. The rise of the pressure with time is shown in Fig. 3.

We mention that the pressure behaviour doesn't depend, in a qualitative sense, on a falling flow value \bar{e}_q . With decrease in \bar{e}_q (i.e. with decrease in the flow reaching the surface), the maximum pressure value decreases, which is a physically proper result. But the curve character remains the same as that shown in Fig. 3 with the difference that the size of the transition region from zero to the saturation level increases.

With the pulse action termination, the pressure dynamics is determined by the solution of the second equation in (22). After the finishing of the pulse action, the essential changes take place. Namely the pressure drops sharply by the value of the light pressure in the pulse. That is, the initial value of the pressure on the second stage is determined by the condition

$$\Pi_2(\theta) = \Pi_1(\theta_\tau) - \Pi_{(q)}. \quad (24)$$

The light pressure at the moment $\theta = \theta_\tau$ can be determined by the relation $q_s(1+R)/c$, where c is the light velocity, and R is the reflection coefficient of a light flow. Then we get $\Pi_{(q)} = \bar{e}_q q_{in}(1+R)/(cP_0) = \bar{e}_q \Pi_q$, where, by estimations, $\Pi_q \sim 10^{-3} \div 10^{-4}$. To determine the constant C_2 , we will use the solution from relations (22) and (23). As a result of this procedure, we get

$$2C_2 = -2\theta_\tau + \frac{\Pi_1(\theta_\tau)}{1 - \bar{e}_q \Pi_q \Pi_1(\theta_\tau)}.$$

Using the estimations made, one can see that the denominator on the right-hand side of the expression for C_2 is always positive and never becomes zero. It is easy to see that, at $\bar{e}_q=0$, the denominator tends to 1 and, when $\bar{e}_q=1$, to some finite value.

Obviously, the real solution for $\Pi(\theta)$ is

$$\Pi(\theta) = \begin{cases} ((\Pi_{in}^{-1} - 2\bar{e}_q^{-1} + \Lambda) \exp(-\bar{e}_q \theta) - \Lambda + 2\bar{e}_q^{-1})^{-1}, & \theta \leq \theta_\tau; \\ \left(2(\theta - \theta_\tau) + \frac{\Pi_1(\theta_\tau)}{1 - \bar{e}_q \Pi_q \Pi_1(\theta_\tau)} \right)^{-1}, & \theta \geq \theta_\tau. \end{cases} \quad (25)$$

This dependence for various \bar{e}_q (various levels of the interaction with radiation) is shown in Fig. 4. Here, we

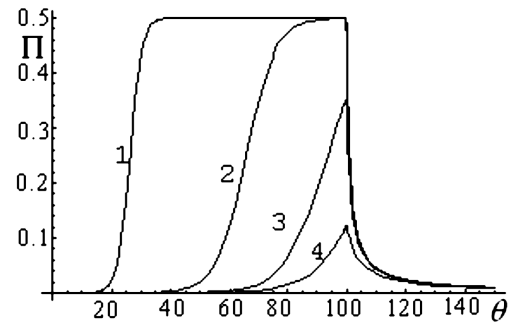


Fig. 4. Gas pressure Π versus time near the surface for different values \bar{e}_q : $\bar{e}_q = 0.6$ (1); 0.2 (2), 0.15 (3), 0.012 (4) for $\tau \sim 10$ fs

considered the situation when the pulse lengths θ_τ are identical.

4. Conclusion

We have considered the dynamics of a plasma torch base under the destructive treatment of the surface of a substance by the intense pulse of radiation. This dynamics is determined, in the general case, by the differential equation (17) or by its dimensionless representation (18) with the boundary condition (6). Our enhanced interest to Eq. (17) (or (18)) is caused by the fact that it determines all the processes which accompany the destruction. On the one hand, it is a boundary condition for Eq. (13) which describes the volume dynamics of the whole torch. On the other hand, it determines the process of development of the so-called corrosive crater, for which the dynamics of its form is described by a differential equation following from the boundary condition (4).

The substantial feature of the explored equation (18) is that it describes the gas phase. That is, the sublimation-type process is examined, when the gas phase arises at once out of the solid phase avoiding a liquid phase. This circumstance requires at least a qualitative formulation of the criterion of that the surface melting does not arise up: $q_{in} > \frac{R_g T_c \rho^{sol} c}{\mu} \frac{1}{1 - R^2}$. For flows which satisfy this inequality, the surface melting does not arise up.

In the technologically actual approximation, when the polytrope exponent tends to unity ($\kappa \rightarrow 1$), Eq. (18) is simplified to (21) and, due to the Heaviside function, is divided into two separate equations, each of them

describes the corresponding part of the process (before the pulse completion and after it).

The general solution of Eq. (21) is found, and its “behaviour” is analyzed (Fig. 4) when taking into account the different levels of the interaction of radiation with a gas-plasma environment which is determined by the factor $\bar{\epsilon}_q$. As seen from Fig. 4, the dependence of the near-surface pressure on time has a correct qualitative behavior, growing to the saturation in the period of action of a pulse and sharply diminishing upon the termination of its action.

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ДИНАМІКА ЛОКАЛЬНО-ФАЗОВИХ ПЕРЕХОДІВ, ЗУМОВЛЕНИХ ІНТЕНСИВНИМ ЛАЗЕРНИМ ВИПРОМІНЮВАННЯМ

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Резюме

Проведено теоретичне дослідження процесу руйнування поверхні твердої речовини під дією потужного імпульсу випромінювання. Із цією метою були вивчені особливості динаміки поверхневого руйнування матеріалу й особливості просторово-часової динаміки газової фази. Ця фаза виникає в результаті локальних фазових змін при швидкому нагріванні поверхні матеріалу лазерним імпульсом, і це приводить до формування (вигорання) корозійного кратера. Отримано диференціальне рівняння, що описує динаміку горіння плазмового факела. Отримано загальний розв'язок рівнянь динаміки плазмово-газової фази й проаналізовано його “поведінку” для різних рівнів взаємодії випромінювання з газом.