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Hydrodynamic efficiency of laser-induced transfer of matter

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***Abstract*. A one-dimensional analytic hydrodynamic model of the direct laser-induced transfer of matter is considered. The efficiency of pulsed laser radiation energy conversion to the kinetic energy of the ejected matter is determined. It is shown that the hydrodynamic efficiency of the process for the layers of matter of thickness exceeding the laser radiation absorption depth is determined by the adiabatic index of the evaporated matter.**

Keywords: *interaction of laser radiation with matter, laser direct printing.*

If an absorbing matter deposited on a transparent substrate is irradiated by sufficiently high-power laser pulses from the substrate side, the matter will be ejected in the direction perpendicular to the substrate. This well-known effect appears because upon the absorption of laser radiation in a layer adjacent to the substrate, the matter is evaporated and, by expanding, plays the role of a piston for the non-evaporated part of matter. In this way, a controllable transfer of various materials: metals, biological materials, polymers, printer's inks, etc., can be performed. In recent years this method of matter transfer was called the laser direct printing or laser-induced forward transfer. It can be applied both for the manufacturing of displays [1], elements of microcircuits and miniature electric power supplies [2] and in polygraphy for colour high-quality printing by viscous inks [3, 4], etc. (see also, for example, [5, 6]).

Although practical applications of laser-induced transfer of matter attract considerable interest, physical processes underlying this effect have not been studied in fact. In this case, unlike, for example, the well-studied evaporation of matter irradiated on the free-surface side [7, 8], the radiation interacts with mater within a closed volume. This should affect the energy threshold of the process at which the transfer of matter begins, the initial ejection velocity of a material, etc. The matter-transfer velocity depends on the efficiency of the acceleration process and can achieve 10^2 m s^{-1} [6]. It can be expressed in terms of the hydrodynamic efficiency – the ratio of the kinetic energy of the accelerated (ejected) matter to the energy supplied to a target. The hydrodynamic efficiency in the case of irradiation of matter on the free-surface side was studied in [9, 10].

In this paper, we consider the one-dimensional hydrodynamic model of the acceleration of matter upon laser evaporation at the boundary with a transparent substrate and determine the efficiency of pulsed laser radiation conversion to the kinetic energy of the ejected matter. Because we neglect the lateral expansion and the influence of boundary effects, the obtained efficiency is the upper limiting value of the efficiency of direct laser-induced transfer of matter far from the energy threshold of this process.

Consider the problem of the acceleration of a plane layer of matter of thickness d and density ρ_0 by a laser beam of intensity q_0. We assume that the half-space $x \leqslant 0$ is filled with a transparent substrate, and laser radiation is uniformly absorbed in the region $x > 0$ in a thin layer of a condensed target of thickness $1/\alpha$, where α is the absorption coefficient. We also assume that the radiation absorption mechanism does not change upon the conversion of matter to the gas phase. In this case, the mass of a layer absorbing radiation remains constant during its hydrodynamic expansion. Consider the case when the radiation intensity q_0 is high enough compared to its threshold value and the energy spent to evaporate matter can be neglected in the total energy balance. Then, we have the problem of the expansion of the specified mass (per unit area)

$$m = \frac{\rho_0}{\alpha} = \int_0^{x_m} \rho(z)\mathrm{d}z,$$

which is restricted from the side $x \geqslant x_m(t)$ by the non-evaporated part of matter M, which can be treated as a rigid heatproof wall of mass $M = \rho_0(d - \alpha^{-1})$ and from the side $x \leqslant 0$ – by an infinitely heavy and absolutely transparent substrate. The change in the laser-beam intensity in the absorbing layer is described by the equation

$$\frac{\mathrm{d}q}{\mathrm{d}x} = -\alpha q_0 \frac{\rho(x)}{\rho_0}, \tag{1}$$

where $\rho(x)$ is the density of the absorbing gas layer.

This formulation of the problem is completely equivalent to the study of the hydrodynamic efficiency of the acceleration of a three-layer thermonuclear target by heavy ion beams in inertial fusion [11]. In [11], a target was considered which consisted of the accelerated layer of a thermonuclear fuel – an absorber in which the main part of the ion energy

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was absorbed, and a tamper – a layer restricting the external expansion of the evaporated absorber. We assume that in our case the tamper is infinitely heavy and absolutely transparent.

The problem has only two characteristic dimensional parameters q_0 and $m = \rho_0/\alpha$ and it belongs to the class of self-similar problems, the situation not being changed when the recoil pressure increasing during the acceleration of the target is taken into account, because no parameters of a new dimensionality are introduced in this case. Note that the problem remains self-similar for any relation between masses of the evaporated and non-evaporated parts of the material.

The expansion of the evaporated mass heated by laser radiation is described by hydrodynamic equations

$$\frac{\partial}{\partial t}\rho + \frac{\partial}{\partial x}(\rho v) = 0,$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(p + \rho v^2) = 0, \tag{2}$$

$$\frac{\partial}{\partial t}\left[\rho\left(\varepsilon + \frac{v^2}{2}\right)\right] + \frac{\partial}{\partial x}\left[\rho v\left(\varepsilon + \frac{v^2}{2}\right) + q\right] = 0,$$

where ρ and v are the density and velocity of the evaporated material, ε is its internal energy, and p is pressure. The equation of state of the gas phase of the material has the form

$$\varepsilon = \frac{1}{\gamma - 1}\frac{p}{\rho},$$

where γ is the adiabatic index. The energy release is described by Eqn (1).

The motion of the non-evaporated part M of the material is described by the equation

$$M\frac{\mathrm{d}u}{\mathrm{d}t} = p|_{x=x_m}, \tag{3}$$

where $u(t)$ is the velocity. The equation of motion written in this form assumes implicitly that the time of propagation of sound or shock waves, which determine the transfer of the momentum and energy of the non-evaporated part of the material, is much shorter than the laser-pulse duration and this part moves as a whole (see details in [10]). The quantity

$$\eta = \frac{1}{2}Mu^2\frac{1}{q_0 t} \tag{4}$$

is the hydrodynamic efficiency of the target acceleration.

Let us introduce the self-similar variable $\lambda = m^{1/2}q_0^{-1/2}\times xt^{-3/2}$ and its functions $R(\lambda)$, $V(\lambda)$, and $P(\lambda)$, which are related to the density, velocity, and pressure in the gas phase by the expressions

$$\rho = q_0^{-1/2}m^{3/2}t^{-3/2}R(\lambda),$$

$$v = q_0^{1/2}m^{-1/2}t^{1/2}V(\lambda), \tag{5}$$

$$p = q_0^{1/2}m^{1/2}t^{-1/2}P(\lambda).$$

A coordinate of the surface of the non-evaporated part of the material is defined in terms of the self-similar variable by the expression

$$x_m(t) = q_0^{1/2}m^{-1/2}t^{3/2}\lambda_m. \tag{6}$$

The system of gas-dynamic equations (2) for new functions can be rewritten in the form

$$\frac{\mathrm{d}}{\mathrm{d}\lambda}\left[R\left(V - \frac{3}{2}\lambda\right)\right] = 0,$$

$$\frac{1}{R}\frac{\mathrm{d}P}{\mathrm{d}\lambda} + \left(V - \frac{3}{2}\lambda\right)\frac{\mathrm{d}V}{\mathrm{d}\lambda} + \frac{V}{2} = 0, \tag{7}$$

$$\frac{1}{\gamma - 1}\left(V - \frac{3}{2}\lambda\right)\frac{\mathrm{d}}{\mathrm{d}\lambda}\frac{P}{R} + \frac{P}{R}\frac{\mathrm{d}V}{\mathrm{d}\lambda} + \frac{1}{\gamma - 1}\frac{P}{R} - 1 = 0.$$

The regularly varying functions of density, velocity and pressure satisfy the relations

$$\int_0^{\lambda_m} R(\lambda')\mathrm{d}\lambda' = 1,$$

$$\frac{1}{2}\int_0^{\lambda_m} RV\mathrm{d}\lambda = P(0) - P(\lambda_m), \tag{8}$$

$$\frac{1}{\gamma - 1}\int_0^{\lambda_m} RV\mathrm{d}\lambda + \frac{1}{2}\int_0^{\lambda_m} RV^2\mathrm{d}\lambda = 1 - P(\lambda_m)V(\lambda_m),$$

which represent the laws of conversion of mass, momentum and energy and are obtained by integrating hydrodynamic equations (2). The first of them is in fact the equation for determining the self-similar variable λ_m. It follows from the velocity continuity condition $v(x_m) = u(t)$ for the hydrodynamic motion at the phase interface that $\lambda_m = \frac{4}{3}\delta P(\lambda_m)$, where $\delta = m/M$. In addition, hydrodynamic efficiency (4) can be now written as $\eta = 2\delta P(\lambda_m)^2$.

Taking the boundary (rigid wall) condition $V(0) = 0$ into account, we have

$$V(\lambda) = \frac{3}{2}\lambda,$$

$$R(\lambda) = \frac{3\gamma - 1}{2(\gamma - 1)}P(\lambda), \tag{9}$$

$$P(\lambda) = P(0)\exp\left(-\frac{3}{16}\frac{3\gamma - 1}{\gamma - 1}\lambda^2\right).$$

Note that solutions of type (9) were earlier discussed in the literature in different formulations of the problems related to the isothermal expansion of matter [12]. Thus, the expansion velocity in solution (9) linearly depends on the spatial coordinate, while the pressure and density decrease according to the Gaussian law. Such a dependence of the gas-dynamic parameters of matter on the spatial variable was obtained in [12] as the limiting self-similar case of the isothermal expansion of a plane layer of matter. Solution (9) shows that this dependence remains also valid for the case when the expanding matter is limited in the space by a rigid accelerated wall moving according to (6).

Consider the balance of the energy supplied to matter. In our formulation of the problem, the laser radiation energy is distributed between the kinetic energies of the non-evaporated (ε_M) and evaporated (ε_m) parts of the irradiated layer and $\varepsilon_M + \varepsilon_m + \varepsilon_T = q_0 t$. The thermal energy

$$\varepsilon_T = \int_0^{x_m} \rho\varepsilon \mathrm{d}x = \frac{2}{3\gamma - 1}\, q_0 t \tag{10}$$

of the expanding material at the instant t is determined from (5), (8), and (9), its kinetic energy is determined by the expression

$$\varepsilon_m = \frac{1}{2}\int_0^{x_m} \rho v^2 \mathrm{d}x = \frac{3(\gamma - 1)}{3\gamma - 1}\left(1 - \frac{2z_m \exp\left(-z_m^2\right)}{\sqrt{\pi}\,\mathrm{erf}(z_m)}\right) q_0 t, \tag{11}$$

where $\mathrm{erf}(z_m)$ is the errors function and z_m can be found from the equation

$$\frac{M}{m} = \alpha h = \frac{\exp\left(-z_m^2\right)}{\sqrt{\pi}\, z_m \mathrm{erf}(z_m)}. \tag{12}$$

In this case, the kinetic energy of the non-evaporated part of the material is

$$\varepsilon_M = \frac{1}{2} M u^2 = \frac{3(\gamma - 1)}{3\gamma - 1}\left(\frac{2z_m \exp\left(-z_m^2\right)}{\sqrt{\pi}\,\mathrm{erf}(z_m)}\right) q_0 t. \tag{13}$$

One can see from (10)–(13) that the thermal energy of the expanding matter is independent of the ratio of the accelerated (M) and evaporated (m) masses of matter (or the ratio of the thickness h of the ejected layer of matter to the absorption length α^{-1}). As this parameter is changed, the redistribution of the kinetic energy between these parts takes place. In the limit of material layers thick compared to the laser radiation absorption length, when $M/m \gg 1$, we have $z_m \approx [m/(2M)]^{1/2} \ll 1$ from (12), and taking into account that $\mathrm{erf}(z_m) \approx 2z_\mathrm{m}/\sqrt{2}$, we obtain

$$\varepsilon_M \approx \frac{3(\gamma - 1)}{3\gamma - 1}\, q_0 t. \tag{14}$$

Thus, all the kinetic energy proves to be concentrated in a layer of the non-evaporated material.

The dependence of the hydrodynamic efficiency on M/m obtained from (4) and (13) is presented in Fig. 1. One can see that in the practically interesting case of the ejection of matter upon evaporation of its narrow layer adjacent to a substrate, i.e. for $M/m \gg 1$, the efficiency weakly depends on this ratio and is close to its limiting value. Thus, if the laser radiation absorption depth is small compared to the thickness of the irradiated layer, the hydrodynamic ejection efficiency can be estimated as

$$\eta_\infty = \frac{3(\gamma - 1)}{3\gamma - 1}, \tag{15}$$

i.e. it is determined only by the value of the adiabatic index in the evaporated matter. Note that upon irradiation of matter from the free-surface side, the hydrodynamic efficiency in this limit tends to zero [9, 10]. In our case, the evaporated material is located between two massive walls, determining the finite limiting value of η_∞.

We considered the energy balance by neglecting the energy spent to evaporate the material and the energy supplied to the transparent substrate. Obviously, the sub-

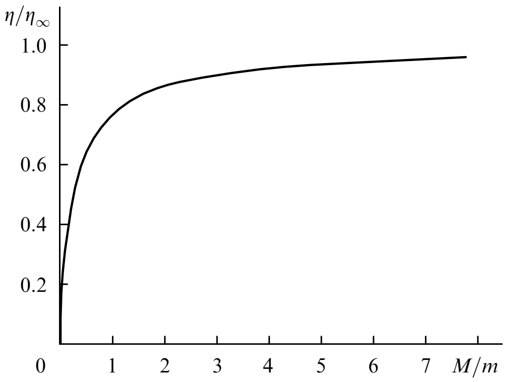

Figure 1. Relative change in the hydrodynamic efficiency of laser-induced transfer of matter as a function of the mass ratio of the accelerated layer and evaporated matter.

limation energy of the matter (where Ω is the specific vaporisation energy) can be neglected if it is considerably lower than the thermal energy of the evaporated material. Therefore, we obtain from (13) the estimate for the laser-pulse energy density $F_\mathrm{p} = q_0\tau_\mathrm{p}$ (τ_p in the pulse duration), which should satisfy the relation $F_\mathrm{p} \gg \varepsilon_\mathrm{ev}(3\gamma - 1)/2$. The elastic energy supplied to the substrate can be neglected if it is considerably lower than the kinetic energy of the expanding matter. In the acoustic approximation, the elastic energy of a wave propagating in a transparent substrate can be estimated as $\varepsilon_\mathrm{el} \sim p_0^2/(2\rho_0 s^2)s\tau_\mathrm{p}$, where p_0 is the pressure at its boundary, ρ_0 is the density of the substrate material, and s is the sound speed in the substrate. By using (5), (9), and (14), we obtain from this for the case $M \gg 1$ of practical interest that $\varepsilon_\mathrm{el}/\varepsilon_M \sim M/(4\rho_0 s\tau_\mathrm{p}) \ll 1$, which is in fact the condition of applicability of the model of acceleration of the non-evaporated matter as a whole.

For such substances as metals, which produce a monatomic vapour upon evaporation, we can assume that $\gamma = 5/3$ and obtain from (15) that $\eta_\infty \approx 50\,\%$. In the case of polymers or viscous printer's inks of composition close to that of polymers, the adiabatic index is generally unknown. In addition, the mechanism of redistribution of the absorbed laser energy, resulting in the decomposition of large carbon-containing molecules and polymer chains in such materials, is not established so far because of the complex chemical composition and numerous reaction and energy relaxation channels. The products of laser ablation were determined only for a few simplest polymers. For example, the products of laser ablation of polyimide are CH, CN, CO, C_2 molecules and other monomers with different bond energies [13], which are found in high excited states after the phase transitions from the condensed state. This means that a considerable part of the deposited energy will be contained in the internal degrees of freedom, and therefore, the effective adiabatic index should be close to unity. The hydrodynamic theory of polymer ablation was developed in [14] and used to analyse experiments on the evaporation of polyimide by radiation from a XeCl laser. The best agreement between the theory and experiment was achieved for $\gamma \approx 1.05 - 1.1$. By assuming that the adiabatic index for viscous printer's inks [4] is close to that found in [14], we obtain the effective hydrodynamic efficiency for them $\eta \approx 10\,\%$.

Thus, we have developed in this paper the one-dimensional analytic theory of laser-induced transfer of matter and determined the maximum efficiency of laser-pulse energy conversion to the kinetic energy of ejected matter. It has been shown that for the layers of matter of thickness exceeding the absorption depth, the conversion efficiency is determined only by the adiabatic index of the evaporated matter.

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