Calculation the efficiency of energy transfer from nanosecond CO$_2$-laser pulses to the iron target during plasma appearance

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Abstract. The steel target evaporation and the gas-dynamic processes were calculated, then followed by the plasma creation on in the metal vapor under the influence of nanosecond pulses were calculated. Mathematical model based on the Euler equations for the inviscid gas flow in conjunction statement with the radiation transfer equation in the diffusion multi-group approximation and the heat equation in solid metal was formulated. Nonlinear evaporation, depending on the energy entering to the target surface, was calculated using analytical expressions for the Knudsen layer. The structures of gas-dynamic flows with the formation of shock waves in an ambient gas (air) in the active vaporization mode and during plasma formation are were studied, also the thermal state of the target is was determined in the one-dimensional formulation. The comparison of the efficiency of energy transfer to the target is was made in both cases, : from laser radiation directly and when plasma appears, by means of thermal radiation. The significant increase in the adsorption coefficient of energy in the case of the appearance of plasma is shown.

1. Introduction

There are many works [1–5] devoted to the study of low-temperature CO$_2$-induced laser plasma. Previously studies were conducted for the laser radiation interaction with matter and attempts were made to use it for surface treatment: cutting, welding, cladding, heat treating. At the high radiation power density $I_{\text{las}} > 10$ MW/cm$^2$, the target material is actively vaporized, and at the vapor near the surface, due to low metal ionization potentials, the plasma is formed, which then propagates towards the beam. This processes has been actively studied both experimentally [2-3] and theoretically [4, 5].

The absorption of laser radiation by metals in the infrared wavelength range, such as a CO$_2$ laser (10.4 μm), is negligible, especially for noble metals. Therefore, the use of such lasers as the energy source for the thermal action on samples does not have high energy efficiency, although, at the same time, it has a number of other advantages. When the plasma occurs, it begins itself to actively absorb the incident radiation, and then emits the stored energy as thermal radiation. If the plasma temperature is sufficiently high (1 eV or higher), then, according to the Hagen – Rouben relationship, the absorption coefficient for photons with the corresponding wavelengths is significant, from 40% for iron to almost complete absorption [6]. As long as the plasma is near the surface, a significant fraction of the radiation from it is directed toward the target and leads to heating of the material. In this paper, we consider the effect of plasma formation on the efficiency of energy transfer from laser radiation to the target for short pulses, its ablation, and the gas-dynamic processes resulting from it.
2. Mathematical model

For the gas dynamics description of the low-temperature plasma, we write the system of equations, without taking into account the viscosity of the gas, consisting of the continuity (1), momentum (2), and energy equations (3):

\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = 0, \quad (1) \]
\[ \frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial P}{\partial x} = 0, \quad (2) \]
\[ \frac{\partial}{\partial t} \left( \frac{3}{2} P + \frac{1}{2} \rho u^2 \right) + \frac{\partial}{\partial x} \left( \frac{3}{2} P + \frac{1}{2} \rho u^2 \right) u = \frac{\partial}{\partial x} \left( Pu \right) - \frac{\partial W}{\partial x} - \frac{\partial G}{\partial x}, \quad (3) \]

where \( \rho \) is the density, \( u \) is the velocity, \( P \) is the pressure, \( T \) is the temperature, \( W \) is the radiation energy flux, \( G \) is the laser radiation intensity.

For the process of mixing vapor with the surrounding air, we used the additional continuity equation per vapor volume fraction:

\[ \frac{\partial \rho_{\gamma_v}}{\partial t} + \frac{\partial \rho_{\gamma_v} u}{\partial x} = 0, \quad (4) \]

supplemented by the relations:

\[ \rho_v = \rho_{\gamma_v}, \quad \rho_g = \rho_{\gamma_g}, \quad \gamma_v + \gamma_g = 1, \]

where \( \gamma_v \) is the vapor volume fraction and \( \gamma_g \) is the gas volume fraction.

In addition to the equations (1-4), the equation of state in the plasma is added: \( P = n_0 k_b T \left( 1 + \alpha \right) \), where \( n_0 \) is the initial concentration of atoms, \( \alpha \) is the degree of ionization.

The plasma is in the local thermodynamic equilibrium (LTE) if the electron concentration in it exceeds the certain critical value \( N_e^{cr} \), determined from the condition: \( N_e^{cr} \geq 1.6 \cdot 10^{12} T_e^{1/2} (\Delta E)^3 \), where \( N_e^{cr} \) is the critical electron concentration (in the \( \text{cm}^{-3} \)), \( T_e \) is the electrons temperature, \( \Delta E \) is the highest energy level in the atom. In this case the degree of ionization are calculated by the Saha ionization equation:

\[ \frac{n_i n_e}{n_a} = 2 \left( \frac{2 \pi m_n k_b T}{h^2} \right)^{3/2} Z_i e^{-\frac{1}{k_b T}} Z_a, \]

where \( Z_a, Z_i \) are the statistical sums for neutral atoms and ions, \( n_i, n_e, n_a \) are the concentrations of ions, electrons and neutral atoms, respectively.

For the radiation losses description, we use the radiation transfer equation in the diffusion multigroup approximation [7]:

\[ -\frac{\partial}{\partial x} \left( \frac{1}{3} c \chi_k(T) \right) \frac{\partial U_k}{\partial x} + c \chi_k(T) U_k = 4 \chi_k(T) \sigma(T, h\nu_k, h\nu_{k+1}) T^4 \quad (5) \]

where \( U \) is the radiation energy density, \( \chi_k \) is the absorption coefficient at the frequency \( \nu_k \), \( \sigma \) is the integral of thermal radiation in the frequency range from \( k \) to \( k + 1 \), \( k = 1, 2, 3, \ldots, \infty \). Then we find the radiation energy flux from the equation:

\[ W_v = -\frac{1}{3} c \chi_v \frac{\partial U_v}{\partial x}. \]

Due to the fact that the radiation transfer equation in the form (5) includes \( U \), which contains only the fraction of the absorbed radiation by the plasma, it is necessary to take into account the incident laser radiation separately. Accordingly, we come to Beer-Lambert-Bouguer law:

\[ \frac{\partial G(x)}{\partial x} - \chi_{las}(x) G(x) = 0, \quad (6) \]

where \( \chi_{las} \) is the adsorption coefficient at the lasers wavelength.
Only the continuous spectrum was taken into account in the radiation absorption coefficient: \( \chi_v^{\text{con}} = \chi_v^{\text{ff}} + \chi_v^{\text{fb}} \), where \( \chi_v^{\text{ff}} \) is the coefficient of the free-free absorption and \( \chi_v^{\text{fb}} \) is the coefficient of the bound–free absorption [8]:

\[
\chi_v^{\text{ff}} = \frac{4}{3} \left( \alpha_0 k_B T \right)^{\frac{1}{2}} \frac{Z^2 e^6}{h c m_v^{\gamma + 1}} n_e n^\nu, \quad \chi_v^{\text{fb}} = \frac{32 \pi^4 e^{10} m_Z^4}{3 \sqrt{3} \hbar^3 c^3 v^\nu} \left( \frac{2 \pi m_e k_B T}{\hbar^3} \right)^{\frac{3}{2}} n_e \sum_{n=1}^{\infty} \frac{e^{\hbar \nu T}}{n^3}. \]

The vapor source is the target material; therefore, it is necessary to calculate its thermal state. It is assumed, that evaporation occurs from the solid phase immediately into the gaseous phase, bypassing the formation of the molten pool, since sufficiently powerful laser pulses with the peak intensity up to \( I_{max} = 86.7 \text{ MW/cm}^2 \) are used. In this case, to calculate the target temperature, we can simply use the heat equation:

\[
c_p \rho \left( \frac{\partial T}{\partial t} - u_x (t) \frac{\partial T}{\partial x} \right) = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{1}{\delta} I_s (t) \exp \left( -\frac{1}{\delta} \cdot x \right), \tag{7}
\]

where \( \delta = \frac{1}{\sqrt{\pi \mu u_s \lambda_v}} \) is the skin depth.

**Boundary conditions.** The target surface reach thermal equilibrium on the radiation with the plasma, since the speed of light \( c \) is much higher than the characteristic rates of gas-dynamic processes. The boundary condition for the radiation energy density on the target-gas boundary is:

\[
cU = \sigma T^4, \quad \text{and on the right (open) boundary, the condition for the free exit of radiation is set as:} \]

\[
W_v = -\frac{cV_v}{2}. \]

For the laser radiation incident on the target surface: \( G(t) = I_0 \exp \left( \int_t^0 \chi_{\text{abs}} \, dx \right) \), while on the open border: \( G = I_0 \). The pulse shape had the triangle form with the duration of 50 ns of the power density growth to the values \( I_{max} = 86.7 \text{ MW/cm}^2 \) followed by linear drop to zero during 250 ns.

In the case of subsonic gas outflow into the open space with atmospheric pressure on the right boundary: \( P = P_{atm} \), and the density and velocity of the gas leaving the region are calculated by the method of characteristics.

For the vapor parameters determination at the target-gas boundary, the Knudsen layer model was used, namely, its analytical approximation, obtained on the solution of the Boltzmann equation for molecular gas flows [9]. As the result, the parameters of the outflowing vapor were determined. The energy conservation condition at the target-gas boundary:

\[
\lambda_s \frac{\partial T}{\partial x} = A_{\ell_s} - \alpha \left( T_p - T_s \right) - cW - |u_s| \rho_s L_v - u(E(0) + pu(0)^2 / 2 + P(0)),
\]

where \( u(0) = M \sqrt{\frac{\gamma RT_s}{\mu}} \) is the vapor velocity, \( u_s \rho_s = u(0) \rho(0) \) is the mass conservation law,

\[
E(0) = \left( \frac{n_v}{\gamma_v - 1} + \frac{n_g}{\gamma_g - 1} \right) kT \]

is equation of state for the vapor, \( P_s = P_{atm} \exp \left[ \frac{\varepsilon / k_b \left( 1/T_b - 1 / T_s \right)}{2} \right] \) is the equilibrium vapor pressure at the target surface temperature \( T_s \).

In turn, the relations for the Mach number and the temperature at the exit from the Knudsen layer:

\[
M = \frac{1 - (P(0)/P_s)^{0.275}}{1 - (\pi_0)^{-0.275}},
\]

\[
\frac{T(0)}{T_s} = \frac{\tau_0 - (\pi_0)^{-0.125} + (1 - \tau_0)(P(0)/P_s)^{-0.125}}{1 - (\pi_0)^{-0.125}},
\]
where \( \tau_0 = 0.20742 \), \( \tau_0 = 0.6437 \).

The thickness of the target is chosen large enough, so that an isothermal boundary condition can be used on its reverse side: \( \frac{dT}{dx} \bigg|_{x=0} = 0 \).

**Initial conditions.** At the initial time, the ambient gas is assumed to be at rest, under normal conditions:

\[
u(x) = 0, \quad P(x) = P_{\text{atm}}, \quad T(x) = T_{\text{atm}}.
\]

### 3. Calculation results

In the process of exposure to pulsed high-power laser radiation, intense heating and active evaporation of the target material occurs. A layer of vapor appears near its surface, pushing out an ambient gas. Figure 1 (a,c) shows the main gas-dynamic parameters of the mixture, including iron vapor and ambient air incoming in the volume at the moment 100 ns. Due to the powerful evaporation process, the vapor velocity is equal to 600 m/s near the boundary, air is completely pushed out from the surface and the shock wave is formed before the vapor moving from the target. The total pressure behind the front of the shock wave is 5-6 atmospheres, and the temperature of the expiring vapor is approaching 3500 K.

![Figure 1](image_url)

**Figure 1.** Main gas-dynamic parameters for vapor-air mixture at 100 ns (a,b) and 1000 ns (c,d). Density of vapor (red), density of air (blue), total density (dash), velocity of mixture (dash-dot) (a,c); temperature (orange), pressure (violet) (b,d).
Near the end of the laser pulse, at moment 250 ns, the evaporation of the target ceases, so the pressure and velocity of the shock wave rapidly decrease. At a time moment of 1000 ns, the velocity of its front decreases almost two times, and the pressure behind it drops to 2.7 atm (figure 1 (c,d)). At the same time the vapor velocity near the target is zero and it has the atmospheric pressure.

The fraction of absorbed radiation during the 300 ns pulse is about 12%. Of this energy, 84% goes deep into the target due to thermal conductivity, 14.4% is spent on heat exchange with the gas phase, 1.6% is spent on ablation (evaporation) of the metal.

With subsequent pulses near the surface, metal vapors gradually accumulate, not having enough time to completely fly away from the surface or condense on it during the time between pulses equal to 10 µs. The concentration of free electrons, which are responsible for the laser radiation absorption, increases, and conditions are created for their avalanche-like growth with quick growth of simultaneous absorption. The incident radiation is actively absorbed followed by the sharp heating and appearance of the plasma. The shock wave, due to rapid heating of the gas (vapor-air), intensifies strongly: the velocity of its front increases up to 1430 m/s, as the pressure behind it to 56 atmospheres (figure 2). The plasma temperature is 12000 K, but it is seriously limited by the powerful flow of relatively cold (4300 K) vapor, coming from the target surface. The vapor velocity near the surface is much more lower in comparison with the situation without plasma. This is due to the huge pressure in the plasma, which significantly suppresses the evaporation of the target material, up to its complete cessation.

![Figure 2](image-url)  
**Figure 2.** Main gas-dynamic parameters with plasma appearance at 100 ns. (a) density of vapor (red), density of air (blue), total density (dash), velocity of mixture (dash-dot); (b) temperature (orange), pressure (violet).

At the moment of the end of the pulse, τ = 300 ns, the plasma moves up to 1 mm from the target and the quasi-one-dimensionality of the problem disappears, because we assumed that the diameter of the evaporation spot is approximately equal to the diameter of the laser beam, which equal 700 µm. At the greater distance from the target, the behavior of the plasma hasn't been studied.

When the plasma appears, a new channel for heat transfer is added due heat radiation from the plasma to the surface. When plasma forms, for a short time almost all the incident laser radiation gets absorbed by the plasma. So the amount of energy transferred directly from the laser beam to the target during 300 ns is only 11%. The fraction of energy that the target receives from plasma is 89%. In this case, heat removal from the surface occurs in the following way: thermal conductivity deep into the target equals 65.5%, 31.5% goes to heat exchange with the gas phase, 2.9% goes to evaporation.

Figure 3 shows comparison the temperatures $T_s$ of the target surface in the modes without plasma and with its presence. The comparison is correct only up to 300 ns, when the quasi-one-dimensionality of the problem is preserved. During this time, the amount of absorbed energy increased 3.2 times from
6 mJ to 19.4 mJ, which corresponds to 12% and 38.8% of the laser pulse energy. Due to the increase in heat exchange with gas phase during plasma existence, the fraction of energy accumulated by the target increased 2.5 times from 5 mJ to 12.7 mJ.

![Figure 3. Comparison of the target surface temperature $T_s$ in the different modes: without formation (dash-dot line) and with the plasma appearance (solid line).](image)

4. Conclusions
With the first laser pulse, when the intensity is insufficient for optical breakdown, active evaporation of the material occurs. Vapors push the ambient gas from the surface and form the front of the shock wave. During the time between pulses the gas-vapor mixture reach dynamic equilibrium, however, vapor gradually accumulates in the area above the target, the electron concentration increases, and conditions sufficient for the plasma formation arise. In this case, the plasma is actively heated, the pressure behind the front of the shock wave increases by an order of magnitude, and the velocity of its front increases several times. Due to the rapid growth of the pressure above the target surface, the evaporation process can be significantly suppressed.

As long as the plasma is near the target, it transfers a significant amount of the thermal radiation into the surface due to the better absorption of short-wave radiation by the iron (from 1 μm or less). As the result, during short pulses (up to 300 ns), the total radiation absorption coefficient for the iron can increase by 3 times, and the amount of heat accumulated by the target by 2.5 times.

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