Thus, by using various experimental configurations parameters of velocity distributions parallel or normal to the flow axis may be analyzed. It follows from analysis of Eqs. (3), (4) that the velocities of the flow core and edge can differ, with it being better to perform observations by the optical heterodyning method.

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EFFECT OF PULSE LENGTH ON EFFICIENCY OF CO_2 LASER INTERACTION WITH A TARGET IN AIR

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UDC 621.373.826:53:62

In the majority of experiments of action of radiation at a wavelength $\lambda = 10.6\ \mu$ on solid targets in air, lasers with a particular pulse output form have been used — namely a powerful leading peak 0.1 μsec in duration followed by a less intense but longer (~1.0 μsec) quasisteady state radiation mode [1, 2].

This study will offer the first detailed investigation of the effect of pulse form and duration $\tau_r \simeq 10^{-7}$-10^{-6} sec upon intensity of gas-dynamic perturbations and the amount of momentum transferred to the target.

The basic energy parameters of the plasma layer and shock wave were defined by the method of [3], based on measurement of characteristics of the shock wave which develops in the cold gas around the target.

The radiation source used was an "LUI-2" high power CO_2 amplifier system with energy of ~1 kJ [4]. Using a wedge-shaped plate 250 mm in diameter made of NaCl, which served as the amplifier output window, multiple reflections from the plate surfaces caused a portion of the radiation to be directed by a spherical mirror and separator plate from a KRS-5 unit to sensors for recording of the pulse energy and form, consisting of a TPI-2-5 impulse calorimeter and a germanium detector [5] with time resolution of ~1 nsec.

Typical oscillograms corresponding to various regimes of amplifier operation are shown in Fig. 1. Pulse 1 is close to a typical CO_2 laser pulse. Pulses 2 and 3 have an identical bell-shaped form and durations differing by a factor of ~10.

The experiments were performed in air at a pressure of 10^5 Pa. The fundamental beam was compressed by a long-focus (F = 250 cm) lens to a section $S_r \simeq 6 \times 7.5$ cm on the surface of the target, formed by a graphite plate with dimensions $0.5 \times 14 \times 18$ cm. In control experiments the value of S_r was varied over the range 4-46 cm². The section was decreased by diaphragming the beam for a fixed energy of $q_r \simeq 15$ J/cm² and constant target dimensions. A ballistic pendulum, the inclination of which was recorded by a video tape recorder, was used to measure the mechanical impulse I_m conveyed to the target. The uncertainty in measurement

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhicheskoi Fiziki, No. 2, pp. 27-30, March-April, 1987. Original article submitted January 14, 1986.

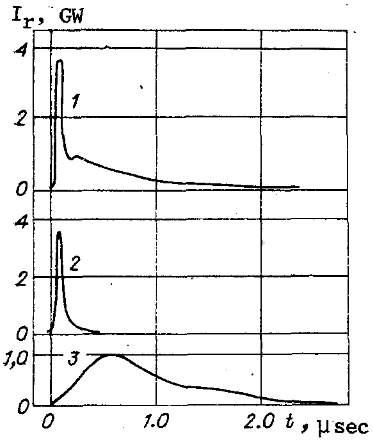

Fig. 1

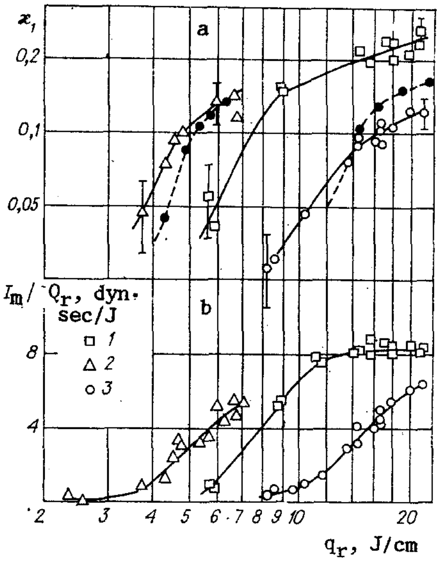

Fig. 2

of I_m did not exceed ~10%. To determine the shock wave energy Q_w, the velocity of the wave front was measured at distances of 68 and 80.5 mm from the target. A dual Toepler–Schlieren system with photoelectric recording was used [3].

It was demonstrated in [2] and the present control experiments that the shock wave maintains a planar form up to a distance $R \leq 1.5d$ (where d is the characteristic transverse dimension of the plasma layer). In analogy to [3], this fact permits determination of Q_w from the measured Mach number on the basis of numerical results for a point explosion performed with consideration of counterpressure and tabulated in [6]. For $S_r = 4$ cm^2 at R = 7-8 cm from the target shock wave propagation corresponds to the theory of a spherical point explosion, while for $S_r \geq 20$ cm^2 it corresponds to planar explosion theory.

Figure 2 shows experimentally measured values of I_m/Q_r and the efficiency $\varkappa_1$ of conversion of laser energy Q_r into Q_w ($\varkappa_1 = Q_{sw}/Q_{sr}$) as functions of q_r. The data points 1-3 correspond to the three regimes of laser operation (see Fig. 1). To calculate Q_w for the conditions recorded in the present experiments $M \lesssim 5$ it was assumed that $\gamma = 1.4$.

The results obtained indicate the strong effect of τ_r on the intensity of gas dynamic perturbations and I_m. Thus, a decrease of τ_r by a factor of 10 times (regimes 2, 3, Fig. 1) leads to a reduction in shock wave formation energy threshold by ~3 times.

Analysis of data similar to that presented in Fig. 2, obtained with $\tau_r = 0.1$-1.0 µsec, various pulse shapes, beam sections $S_r = 4$-46 cm^2 and $q_r = 3$-20 J/cm^2 revealed that within the limits of experimental scattering the amount of mechanical impulse is defined only by the shock wave parameters. The dependence of I_m/Q_w upon shock wave energy referenced to the transverse section of the plasma piston S_r is shown in Fig. 3. Points 1-3 were obtained for $S_r = 46$ cm^2; 4 and 5, for $S_r = 4$ cm^2; 1 and 4, in regime 1; 2, regime 2; 3 and 5, regime 3 (Fig. 1). The experimental results shown in Fig. 3 indicate that the specific mechanical momentum is functionally related to the energy characteristics of the shock wave by the expression $I_m/Q_w = f(Q_w/S_r)$ and is independent of the method whereby the gas dynamic perturbation is created.

Two stages can be distinguished in the formation of momentum transfer to the target during laser pulse action. In the first, over a time $\sim\tau_r$, the radiant energy, being partially absorbed, forms a plasma layer, while in the second stage, during shock wave propagation over the characteristic relaxation time τ_p a transfer of momentum to the solid body occurs. The quantity I_m depends on both the coefficient of radiation absorption in the plasma k_1 and the efficiency of plasma layer energy conversion to shock wave energy k_2.

The radiant energy transmitted by the shock wave can be estimated from the expression

$$Q_w \simeq k_1 k_2 \int_{t_1}^{\infty} \int_{S_r} I_r/S_r \cdot dt\, ds,$$

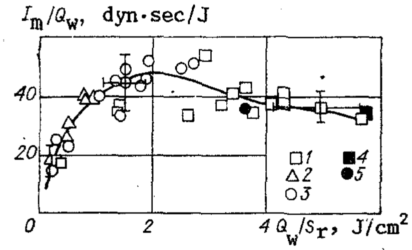

Fig. 3

where t_1 is the moment of formation of the laser plasma at the surface of the opaque obstacle, defined in [7] by the condition

$$t_1^{-1/2}\int_0^{t_1} I_r/S_r\cdot dt \simeq 10\ \text{J/cm}^2\cdot\mu\text{sec}^{1/2}$$

at $k_1 \approx 0.5$ [2], $k_2 \approx 0.56$ [3]. As was shown in [3] the value of k_2 is practically independent of plasma creation conditions.

Calculated values of $\varkappa = Q_w/Q_r$ for two pulses of similar form differing by a factor of ~10 times in their duration (regimes 2 and 3 of Fig. 1) is shown by the dashed lines of Fig. 2a. The correspondence between calculated and experimental data can be considered good, considering the approximate character of the estimate. Thus, the analysis performed indicates that in the energy range $q_r \approx 3$-20 J/cm² increase in pulse duration within the range 0.1-1.0 μsec produces a reduction in shock wave energy due to an increase in the fraction of radiant energy absorbed by the target before the time of plasma formation. We note that at $\tau_r \approx 10^{-6}$ sec the presence of a leading peak which accelerates plasma formation leads to an increase in $\varkappa_1$.

It was stated in [8] that the maximum value of impulse transferable to an infinite plane $(I_m/Q_w)_{max} \approx 70$-$90$ dyn·sec/J is reached at the time $t \approx 0.5\tau_p$, where $\tau_p = (2Q_w/p)^{1/3}\gamma^{1/2}/c$ is the relaxation time of a spherical shock wave propagating in a semispace. The similar values of $(I_m/Q_w)_{max} \approx 128$ dyn·sec/J for spherical and $(I_m/Q_w)_{max} \approx 136$ dyn·sec/J for the planar case were obtained by numerical integration of the functions p(r, t) tabulated in [6]. At large transverse target dimensions I_m begins to decrease after reaching a maximum. This is caused by the negative phase of the pressure. The final value of I_{m_∞}, as is shown by the calculations of [8], is 5-10 times less than $I_{m_{max}}$. Attenuation of the effect of the negative phase can be produced by choosing an optimum transverse target dimension $D \sim R_r$, comparable in scale to the shock wave relaxation [1, 2]. In this case a collapse of the rarefied zone, not considered in [8], occurs upon exit of the shock wave front to the body surface. The maximum experimental value of specific impulse (see Fig. 3) proves to be ~2 times less than the theoretical value.

It should be noted that the characteristic scale R_r of shock wave relaxation under our experimental conditions, as can be shown by simple calculations, defines a spherical front form at large distances from the target $R_r = (2Q_w/p)^{1/3}$. Thus for a maximum shock wave energy under our conditions ($Q_w \approx 300$ J), $R_r \approx 18$ cm. The major portion of impulse transfer to the solid body in the range studied $Q_w \approx 10$-300 J should occur during shock wave propagation at a distance $R \approx 0.5R_r \lesssim 9$ cm, i.e., comparable to the characteristic target radius. However the shock wave propagates as in a planar explosion up to $R \approx 1.5d \approx 10$ cm for $d \approx 7$ cm. Thus it can be proposed that the major portion of the time required for impulse transfer to the solid body during pressure relaxation at its surface is determined by the one-dimensional character of shock wave front propagation. Apparently this is due to the experimentally observed (see Fig. 3) dependence of specific impulse transfer on the parameter Q_w/S_r, which characterizes the intensity of the planar shock wave.

Regarding the concrete form of the dependence $I_m/Q_w = f(Q_w/S_r)$, one may note the significant effect of the target driving process, which has not been considered previously in studying formation of impulse transfer under laser action. A similar process has been studied in detail in investigations of acceleration of metal plates by detonation products (see, e.g., [10]). The plate takes on velocity in bursts, and achieves steady-state motion after multiple passage of compression and rarefaction waves through it. With decrease in Q_w the time during which high pressure exists near the target surface, t, becomes comparable to the wave propagation time through the target, which considering the elements of which it is composed, comprises $\tau_m \approx 2\ell_m/c_m \approx 2\cdot10^{-5}$ sec (where ℓ_m and c_m are the thickness and speed of sound in the target). Using the self-similar solution for a planar shock wave to evaluate t:

$$t = (p_0/p)^{3/2}\left[\frac{8}{9(\gamma+1)}\right]^{3/2}\frac{2Q_W}{\alpha S_r p_0 c}\gamma^{1/2},$$

where c is the speed of sound in air under normal conditions at $p_0 \approx 10^5$ Pa, $\gamma = 1.4$; $\alpha = 1.077$ [6]. At a radiant power of $I_r \lesssim 10^7$ W/cm² the initial pressure in the laser plasma exceeds atmospheric by a factor of ~50 times [9]. The characteristic time required for decrease of p by a factor of 10 to $p/p_0 \approx 5$ for $Q_W/S_r = 0.25$-1.0 J/cm² is then equal to $t \approx 5\cdot10^{-6}$-$2\cdot10^{-5}$ sec. This means that for $Q_W/S_r \lesssim 1$ J/cm² the condition $t \lesssim \tau_m$ is satisfied. In this case a significant portion of the energy can be concentrated in deformation waves periodically reflected from the plate surface, and the efficiency of acceleration of the target as a whole is decreased by ~2 times [10]. Apparently it is this process which produces the experimentally observed (see Fig. 3) decrease in specific momentum transfer for low energy densities $Q_W/S_r \lesssim$ 1 J/cm².

Thus, the present study has for the first time investigated the effect of duration of radiation at $\lambda = 10.6$ µm ($\tau_r \approx 1.0$-0.1 µsec) on the value of impulse transferred to the target. It has been shown that reduction in shock wave energy with increase in τ_r is caused by additional radiant energy losses to target heating. It has been established experimentally that the amount of impulse transferred is determined unambiguously by the shock wave parameters and is independent of shock wave formation conditions. Consequently, the dependence $I_m/Q_W = f(Q_W/S_r)$ (see Fig. 3) defines limiting values of I_m which can be obtained in practice with consideration of the efficiency of radiation conversion into shock wave energy.

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