EFFECT OF IMPULSIVE EROSION FLAME PARAMETERS ON PRESSURE PULSATIONS

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Results of a numerical modeling of the gas dynamics of erosion product escape during action of millisecond-long laser pulses on the surface of metal and dielectric targets were presented in [1]. The experimental complex and a numerical modeling method based on the full system of Navier–Stokes equations were described. Calculated data were compared to the experiment for various overpressures. It was shown that the pressure pulsations on targets irradiated by a laser are gas dynamic in nature.

The present study will consider the behavior of target pressure pulsations as a function of gas dynamic parameters of the erosion flame.

In reducing the system of equations to dimensionless form [1] made use of parameters at the nozzle section: dimensionless time $t' = tu_s/r_s$ (where r_s is the radius of the irradiated spot (sonic nozzle), u_s is the initial departure velocity of the erosion products from the irradiated spot (at the sonic nozzle section). Moreover, the flow is defined by: $n = p_s/p_\infty$, the overpressure (ratio of pressure at the nozzle section to pressure in the submerged space), T_s/T_∞, the ratio of the temperature at the nozzle section and in the submerged space, Re_s, the the Reynolds number, γ, the adiabatic ratio, M_s, the Mach number at the nozzle section, and r_t/r_s, the ratio of the target and irradiated spot radii.

For various irradiated spot sizes calculated curves of pressure pulsations as a function of dimensionless time are identical for other parameters equal. Upon transition to dimensional quantities, the dimensionless time must be multiplied by r_s/u_s, which means that the pulsation frequency is proportional to u_s and inversely proportional to r_s. Since the pulsations are irregular in nature, by frequency we understand here the number of pulsations within a defined time interval, for example, the duration of the laser pulse. Thus, while maintaining the form of the irradiated material, the laser pulse flux density on the target, the overpressure, and other parameters, but changing the irradiated spot radius by a factor of k times, we can expect a change in pulsation frequency by a factor of 1/k times. Figure 1 shows results of experiments on irradiation of two different dielectric targets, which demonstrate the validity of this conclusion. Curves 1, 3 correspond to an irradiated spot radius of 7 mm, while curves 2 and 4 are for 3.5 mm, i.e., $r_s/r_s' = 2$. In this case the pulsation frequency also changes by a factor of two times.

Another defining parameter of pulsation frequency, which depends on several factors is $u_s \sim M_s\sqrt{T_s/m}$ (m is the mass of the particles (atoms) of the evaporated material). One of the assumptions used in the calculations is that the temperature in the irradiated spot is proportional (and close in value) to the boiling point of the evaporating material, i.e., under the action of the laser pulse the temperature of the boiling surface is not markedly increased. Since the temperature at the nozzle section enters into the calculation not only through the speed, but directly, it can affect the behavior of pressure pulsations significantly.

To study this phenomenon a series of calculations were performed with different temperature ratios T_s/T_∞ (for $T_\infty = 300$ K) with other conditions identical. The calculation results are shown in Fig. 2, which shows curves of total normalized pressure on the target surface $\hat{p}$ [1] as a function of time for various ratios T_s/T_∞. As was proposed, the pulsations depend significantly on temperature as regards both frequency and amplitude. Calculations were performed mainly for $\gamma = 1.4$. The dashed curve is the pressure on the target vs time for $\gamma = 1.67$ for the jet and 1.4 for the external gas. In the calculations the jet boundary was taken as the line on which $T = T_{max}$ (jet T-boundary) [2], and in calculations the adiabatic index was changed at points on the boundary. Apparently because of changes in jet parameters the

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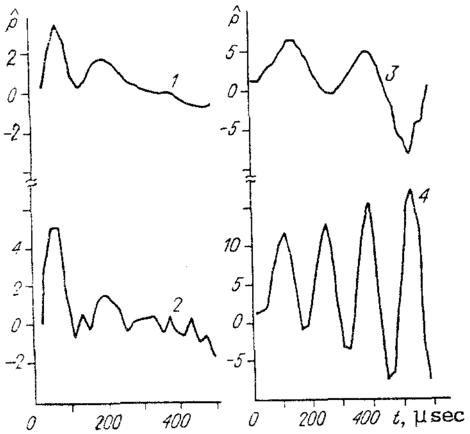

Fig. 1

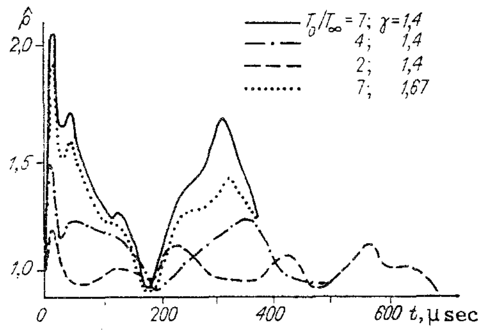

Fig. 2

pulsation curves differ somewhat, but on the whole the adiabatic index does not play a significant role in pulsation behavior.

Another parameter which defines the initial velocity of the evaporation particles is the mass of the atoms (molecules) of the evaporating material, this quantity being used only in finding dimensional time. For other initial parameters equal, it affects the pressure curve only by expanding or compressing the time axis. Thus, it can be expected that for materials with similar boiling points but significantly different atomic (molecular) mass, the pulsation frequency will differ by the square root of the mass ratio, with the frequency being higher for the lighter substance. Note that the effect of mass may prove to be somewhat complex, since it was assumed in the calculations that the mass of the flame atoms and the inundated space were the same, while in the experimental studies the erosion products of the various material escaped into air. To verify the effect of flame atom mass on pulsation frequency experiments used Al (boiling point T_b = 2721 K, m = 27 at. units) and Sn (T_b = 2995 K, m = 118.7 at. units) with similar boiling points but significantly different masses. An estimate indicates that the pulsation frequencies for those materials should differ by a factor of approximately two times.

Figure 3 shows experimental curves of pressure pulsations $\hat{p}$ on the target as a function of time for Al and Sn (curves 1, 3). The experiments were carried out under identical conditions (overpressure, irradiated spot size, etc.) for all curves. As was predicted, the pulsation frequencies for these curves differ by almost two times. An even lower pulsation frequency is found for irradiation of a lead target with T_b = 2017 K, m = 207.2 at. units (curve 4). Curve 2 was obtained with a magnesium target (T_b = 1380 K, m = 24.3 at. units). The masses of Mg and Al are close, but their boiling points differ significantly. An estimate with time normalization indicates the pulsation frequency for magnesium should be lower than for aluminum by a factor of 1.3 times.

As is evident from Fig. 3, in the experiment there is a tendency to reduction in frequency. However, we note first that it is difficult to choose materials with similar atomic masses and greatly differing boiling points (a difference in boiling point by a factor of two produces a frequency change by $\sqrt{2}$ times, which is not too noticeable in experiment). Second, as was already noted above, the temperature dependence of pulsations is significantly more complicated than the mass dependence. Aside from the time normalization, temperature appears directly in the calculations. Thus, to maintain the overpressure at a definite level, it is necessary to decrease the density of the jet with increase in temperature, which strongly affects the gas dynamics. We should also note the effect of the Mach number on pressure pulsations. The greater part of the calculations were performed with the assumption that the erosion flame was a sonic nozzle, i.e., $M_s = 1$. This corresponds to a regime of intense target material evaporation where the vapor flow reaches sonic velocity [3]. The case $M_s > 1$ cannot be realized, since there is no supersonic nozzle to drive the evaporated material. For a weak evaporation regime, where the overpressure is low, there is no doubt that $M_s < 1$. To clarify the effect of M_s on pressure pulsations, gas dynamics calculations were performed for small overpressures and $M_s = 0.5$ and 1. In Fig. 4 the solid curve shows pressure pulsations on the target for n = 1.1, $T_s/T_\infty = 2$, Re = 10^3, $r_t/r_s = 2$ and $M_s = 0.5$. The dashed line is for a jet with $M_s = 1$ (other parameters the same). When M_s is halved, the pulsation amplitude changes, but the general form of the curve remains the same. The small additional

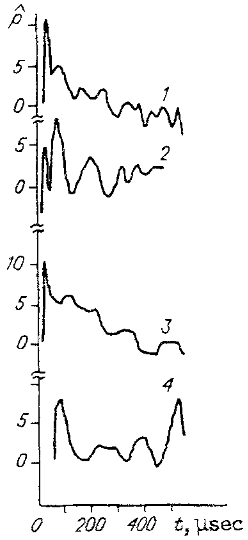

Fig. 3

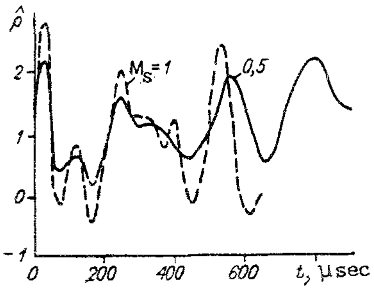

Fig. 4

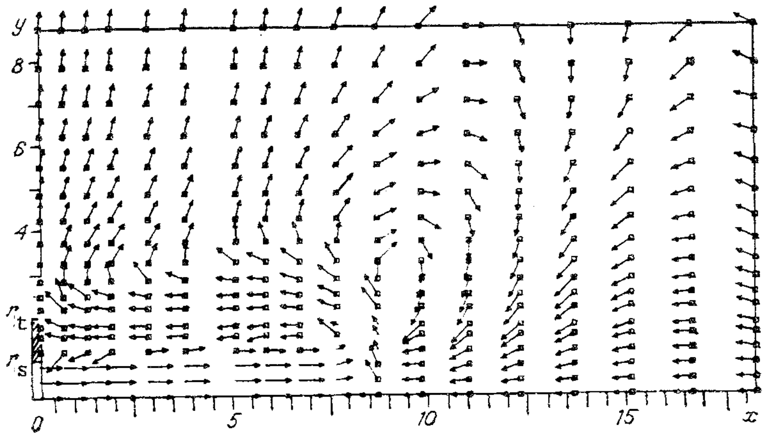

Fig. 5

peak at 400 μsec can be explained by the flow field pattern. The flow field for the time 300 μsec is shown in Fig. 5 using the notation of [1]. For intrasonic escape from the surface the jet unfolds, with its frontal portion recalling the characteristic pattern of turbulent flows for a jet of low-density gas into a higher density gas [4], called a "cocoon" by the authors of that study. In the case shown in Figs. 4, 5 and $M_s = 0.5$ jet unfolding begins 200 μsec after nozzle turn-on, while by 400 μsec the disturbance from the back flow reaches the target surface, which causes an additional pressure flare. On the whole, we can assume that the calculations with $M_s = 1$ reflect the behavior of pressure pulsations qualitatively correctly for weak evaporation as well, which agrees with the experimental data of [5], where the intensity of irradiation of a dielectric target was varied over almost two orders of magnitude.

Of the jet parameters considered in the calculation, we have yet to describe the effect of viscosity or Re_s on pressure pulsations. Note that for different Re_s the flow fields are identical. In the Navier–Stokes equations $Re_s = \rho_s u_s r_s / \mu_s$, where ρ_s, μ_s are the density and viscosity at the nozzle section [6]. As was noted above, it is assumed that the developed evaporation regime (jet turn-on) arises when the surface attains the boiling point. In this case μ_s and r_s are specified constants, while, ρ_s and u_s depend significantly on the power of the laser pulse. For weak evaporation (low overpressure) ρ_s and u_s are lower than at high radiation intensities (high overpressures), so that Re_s is also lower. Moreover, for other conditions equal (overpressure, target size, surface temperature) Re_s will be lower for an evaporated material with higher viscosity. Figure 6 shows calculated curves of pressure pulsations vs time for $n = 2$, $T_s/T_\infty = 2$, $r_t/r_s = 2$, $\gamma = 1.4$, and $Re_s = 10^3$ (solid curve) and 10^5 (dashes). The following tendency can be seen: with a decrease in Re_s individual weak pulsations disappear, with a consequent reduction in pulsation frequency, which is possible for weak evaporation or a material with high viscosity.

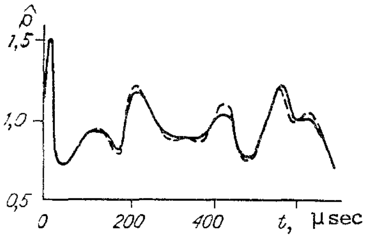

Fig. 6

Thus, calculation of the gas dynamics of material evaporation under the action of a laser pulse has allowed analysis of the effect of the characteristic jet parameters and physical properties of the target material upon the behavior of pressure pulsations. A decrease in pulsation frequency was predicted and observed experimentally with increase in irradiated spot size and growth in evaporated particle mass, as was significant dependence of the form of the pulsation curve upon the ratio of the temperatures of the irradiated spot and the inundated space. A study has been made of the effect of such jet parameters as γ, Re_s, and M_s, which, as calculations have shown, have a weak effect on the behavior of pressure pulsations of the irradiated target.

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