EFFECT OF EXTERNAL CONDITIONS ON THE FORMATION OF PRESSURE PULSATIONS ON A TARGET IRRADIATED BY A LASER

N. M. Bulgakova
and L. I. Kuznetsov

UDC 533.6.011:535.211

Bulgakova and Kuznetsov [1] examined the results of experimental investigations and a numerical modeling based on the complete system of Navier–Stokes equations to establish the gas-dynamic pattern of dispersal of erosion products from the irradiation of metallic and dielectric targets by a submillisecond laser. It was found that the pressure pulsations on the targets were of gas-dynamic nature. In [2], an analysis was made of the effect of the gas-dynamic parameters of an impulsive erosive jet and the target material on the pattern of flow and the formation of pressure pulsations on the irradiated target.

Here, we present results of theoretical and experimental studies of the dependence of the behavior of pressure pulsations on an irradiated target on the external parameters in the formation of the erosive jet: the pressure and species of the gaseous medium and the dimensions of the nonirradiated part of the target.

As was shown in [3], other conditions being equal, a decrease in ambient pressure p_∞ is accompanied by a decrease in the amplitude of the fluctuation component of the total pressure on the target. At $p_\infty = 10^2$-10^3 Pa, the curves of total pressure become nearly smooth. This empirical result is fully consistent with the gas-dynamic description of the process, since it is the motion of the gas of the submerged space near the nonirradiated edge of the target that determines the fluctuation of total pressure. With a decrease in p_∞, the strong effect of this motion at the edge of the target decreases compared to the contribution of the reaction of the jet. On the other hand, a decrease in p_∞ is also accompanied by conservative behavior of the amplitude of the remaining weak pulsations of total pressure normalized for p_∞ [1].

In the calculations in [1, 2], the initial equations were reduced to dimensionless form and the pressures p_e and p_∞ were represented in the form $n = p_e/p_\infty$ (n is the degree of underexpansion and p_e is the pressure on the edge of the nozzle). The degree of underexpansion can be kept constant while p_e and p_∞ are varied. For example, p_e and p_∞ can be reduced in these cases. Thus, the results of calculations will be identical within a broad range of p_e and p_∞ for the same degree of underexpansion and constant values of the other dimensionless parameters.

Figure 1 shows results of measurement of the pressure pulsations $\hat{P}$ on an ebonite target for n = 2, 10, 20, 40, and 80 (a-e). These results were obtained with a fixed value $p_\infty = 10^5$ Pa and variation of $p_e = (2, 10, 20, 40, 80)\cdot 10^5$ Pa. These values correspond to laser-radiation energy densities E_0/S = 140, 400, 650, 1100, and 1800 J/cm^2 (top curves). The corresponding degrees of underexpansion with a fixed value $p_e = 2\cdot 10^5$ Pa (E_0/S = 140 J/cm^2) were obtained by decreasing the ambient pressure: $p_\infty = (20, 10, 5, 2.5)\cdot 10^3$ Pa (bottom curves).

In the computer analysis of the experimental results, the total pressure on the target was normalized with respect to the pressure in the radiation spot [1]. Scaling of the curves so that the y-axis was proportional to the degree of underexpansion made it possible to renormalize the pressure pulsations with respect to p_∞. This in turn made it possible to obtain the dimensions of the pressure pulsations on curves constructed relative to ambient pressure.

There was a great variation in the conditions under which the laser radiation passed through the erosive jet when different radiation energies and ambient pressures were used. These variations could have in turn led to significant differences in the energy and shape of the laser pulse reaching the target surface. In order to correctly establish the signal representing the pressure on the targets, we made a computer correction of the measurements to allow for attenuation of the radiation in the jet [4]. Making such a correction is partic-

---

Novosibirsk. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 1, pp. 65-69, January-February, 1993. Original article submitted November 11, 1991.

 0021-8944/93/3401-0062$12.50

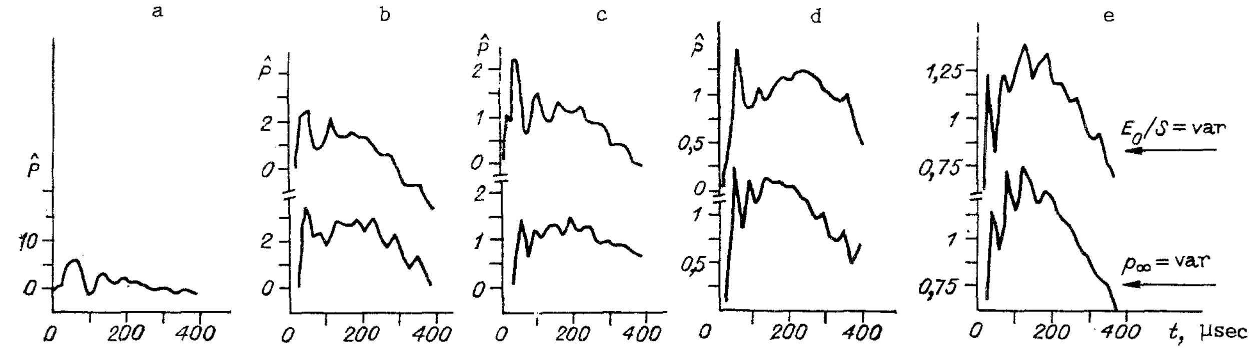

Fig. 1

ularly important in the case of large n, when a comparison is being made between regimes with high values of p_e and E_0/S (discharge of the jet into the atmosphere) and regimes with low p_e (discharge into a low-density gas).

As can be seen from Fig. 1, there is a close resemblance between pairs of curves of pressure pulsation $\hat{P}$ obtained with greatly differing radiation energies and ambient pressures but constant values for the degree of underexpansion and the other radiation parameters (the target material, the dimensions of the radiation spot and target, the composition of the surrounding medium, etc.). Together with the calculations, this empirical finding confirms the decisive role of the gas-dynamic mechanism in the formation of the pressure pulsations on the irradiated target.

It is apparent from the flow-field patterns [1, 2] that the gas of the surrounding space actively participates in the formation of the pressure pulsations on the target and that its physical properties should also influence these variations.

As for the gas of the erosive jet [2], the most important parameters of the gas of the surrounding space are temperature T_∞ and molecular weight m_∞. These parameters characterize the mobility of the gas (its thermal velocity $u_\infty \sim \sqrt{T_\infty/m_\infty}$), i.e., its ability to react to a disturbance of the jet. Thus, the same parameters also determine the pressure pulsations. Since we did not consider diffusion in the numerical solution of the complete system of Navier–Stokes equations, it was not possible to obtain the flow pattern and the pattern of pressure pulsations on the target for different species (molecular weights) of gases in the jet and the surrounding space. However, as noted above, if we take the thermal velocity of the molecules as the main parameter, then the discharge of a jet into a gas with a different molecular weight can be modeled in a first approximation through a corresponding change in its temperature. For example, if we were to examine the discharge of an erosive jet with $m_e \approx 29$ amu into air or helium with identical T_∞ but molecular weights differing by a factor of seven, we could model this process as the discharge of the jet into gases with an identical molecular weight equal to that of air but have a temperature for helium that was seven times greater. Figure 2a shows results of calculations of the pressure pulsations on the given target for an erosive jet with $m_\infty = 29$ amu, $T_e = 600$ K, $p_e = 2 \cdot 10^5$ Pa, and $\gamma_e = 1.67$ and a surrounding gas with $m_\infty = 29$ amu, $p_\infty = 10^5$ Pa, $\gamma_\infty = 1.67$, and $T_\infty = 300$ and 2100 K (lines 1 and 2). Here and in the calculations, we assigned $Re = 10^3$, $M_e = 1$. A similar result was obtained in the experiments (Fig. 2b, lines 1 and 2 – air, helium). The frequency of the pulsations produced by the laser irradiation of a dielectric target in air is lower than under similar conditions in helium. This finding has been confirmed for other target materials such as magnesium [4]. There is also a decrease in the amplitude of the pulsations in the case of a helium atmosphere (Fig. 2b).

The dashed line in Fig. 2a represents the pressure pulsations obtained in a calculation performed for conditions analogous to those for curve 2 but with $\gamma_\infty = 1.4$. Thus, as in the case of variation of the adiabatic exponent of the material in an erosive jet [2], this parameter has relatively little effect on the pulsations.

Figure 3 shows the theoretical flow field corresponding to Fig. 2a, when $T_\infty = 2100$ K, $T_e = 600$ K. The field is shown for the moment of time t = 280 μsec. A structure referred to as a cocoon by Smarr et al., [5] develops under these conditions. The same structure was obtained in [2] in the case of subsonic discharge ($M_e = 0.5$) into a surrounding gas with a lower temperature ($T_e/T_\infty = 2$).

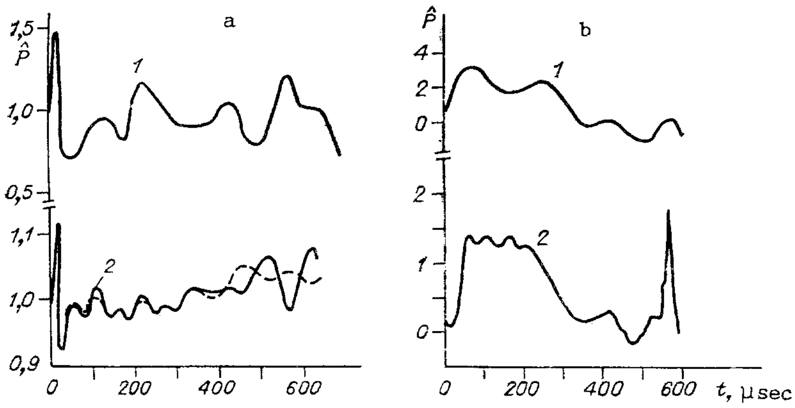

Fig. 2

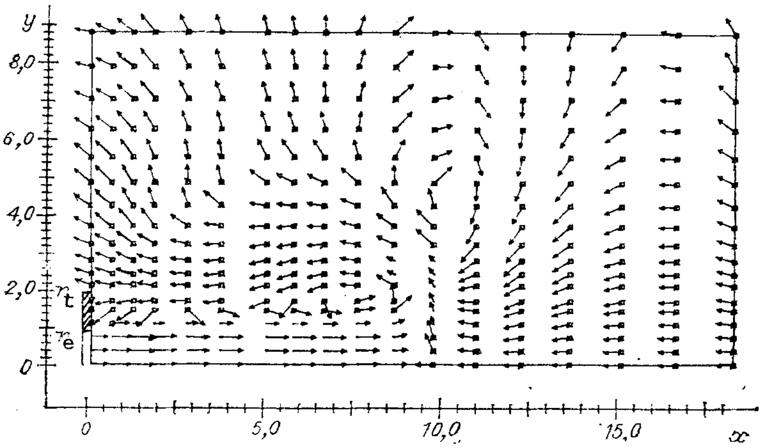

Fig. 3

The effect of the dimensions of the nonirradiated edge of the target on the pressure pulsations should also be considered in the calculation. With a target radius r_t equal to the radius of the radiation spot r_e, the pressure on the target [1] normalized with respect to the reaction of the jet p_j is represented as a straight line $\hat{P} = 1$ in the calculation after formation of the jet. With the appearance of the nonirradiated edge of the target, i.e., with a fixed value of r_e and an increase in r_t, the gas around the target that is brought into motion subjects this edge to an additional load [1]. The dashed line in Fig. 4a shows the calculated total normalized pressure $\hat{P}$ on the target with $r_t = 2r_e$, $n = 2$, and $T_e/T_\infty = 2$. The pressure pulsations increase even more with further increase in r_t/r_e, an increase in amplitude being seen during irradiation. At $r_t/r_e \geq 8$ (the solid curve in Fig. 4a), the behavior of the pulsations remains nearly constant. When an infinite solid wall adjacent to the radiation spot is introduced in the calculations, the pattern of pulsation differs little from the case $r_t/r_e = 8$. It should be emphasized that this ratio was obtained for specific values of n and T_e/T_∞ and may be different for different conditions.

A similar pattern was seen in the experiment. Figure 4b shows curves of normalized total pressure on ebonite targets with $E_0/S \simeq 120$ J/cm², $n \simeq 2$, $T_e/T_\infty \simeq 2$, and $r_e = 3$ mm. No significant pressure pulsations are seen on the curve at $r_t \simeq r_e$. Pronounced pressure pulsations are seen at $r_t = 2r_e$, these pulsations becoming even greater at $r_t = 3r_e$. The frequency of the pulsations decreases at $r_t \geq 4.5r_e$, while the amplitude increases and continues to increase with time. Qualitatively speaking, this result agrees completely with the calculated results examined above. Similar results were also obtained for metal targets, such as titanium.

In conclusion, it should be noted that gas-dynamic calculation of the intensive vaporization of the surface of a specimen irradiated by a laser pulse makes it possible to fully analyze the effect of external conditions on the behavior of pressure pulsations on the target. get. In particular, it was shown that the pressure of the submerged space has a significant effect on the amplitude of these pulsations and that the frequency and amplitude of the latter are dependent on the parameters of the gas in this space and the dimensions of the irradiated target. Together with the results in [1, 2], the gas-dynamic model of the formation of

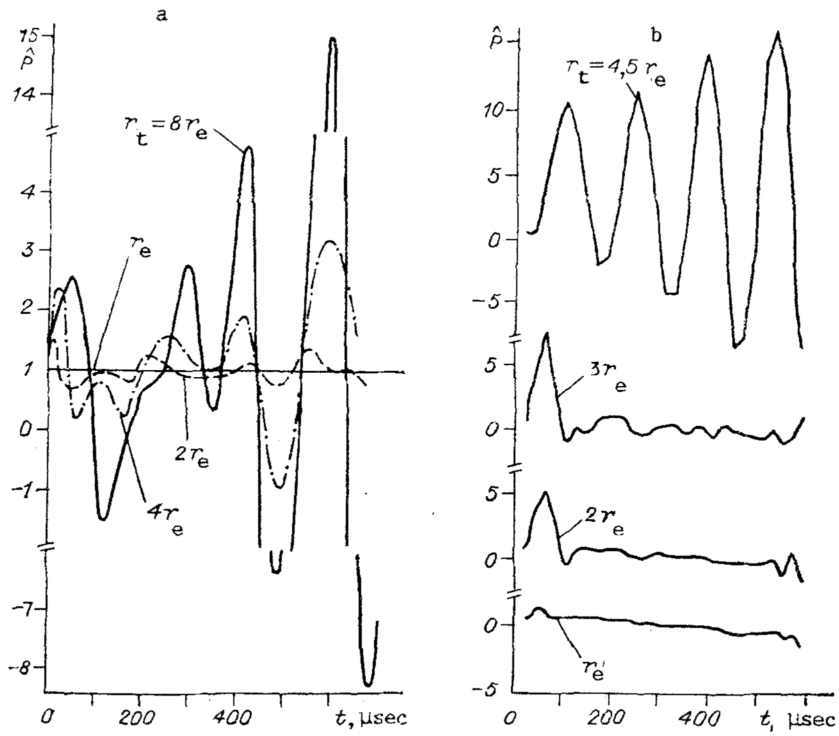

Fig. 4

pressure pulsations on an irradiated target permits detailed study of the flow pattern and the effect of the radiation parameters, material properties, and external conditions on the pressure pulsations which develop on a specimen during intensive laser radiation.

LITERATURE CITED

1. N. M. Bulgakova and L. I. Kuznetsov, "Gas dynamics of impulsive jets and pressure oscillations on a target irradiated by a laser," Prikl. Mekh. Tekh. Fiz., No. 6 (1992).
2. N. M. Bulgakova and L. I. Kuznetsov, "Effect of the parameters of an impulsive erosive jet on pressure pulsations," ibid., No. 6 (1992).
3. L. I. Kuznetsov, "Transfer of a pressure to metallic and dielectric targets irradiated by a neodymium laser in the free-generation regime," ibid., No. 6 (1991).
4. L. I. Kuznetsov, "Interaction of an erosive jet and the surrounding medium," Izv. Akad. Nauk SSSR, Ser. Fiz., 55, No. 6 (1991).
5. L. L. Smarr, M. L. Norman, and K.-H. A. Winkler, "Shocks, interfaces, and patterns in supersonic jets," Physica Sect. D. Nonlinear Phenomena, 12, (1984).