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DYNAMICS OF A SHOCK WAVE IN LASER-INDUCED SURFACE AIR BREAKDOWN

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The amplitude and the time of arrival of a shock wave have been measured experimentally and calculated numerically at different distances from the region of the surface air breakdown by the radiation of a single-pulse YAG:Nd^{3+} laser for energy densities of 2.5–570 J/cm^2. Good agreement between the experimental and calculated values of the shock-wave amplitude beyond the breakdown region has been established. A more rapid propagation of the actual shock wave as compared to the calculated shock wave has been revealed for low energies of laser pulses, whereas a retarded propagation of the actual shock wave as compared to the calculated one has been revealed for high energies.

The action of pulse laser radiation with a power density of $q \gtrsim 10^6$ W/cm^2 on metal targets in air leads to the evaporation of the target and the formation of a surface laser plasma which begins, as a rule, in the target vapor and moves into the air as the power density grows above $5 \cdot 10^6$ W/cm^2 at a laser-radiation wavelength of ~1 μm [1–5]. For higher densities of the laser-radiation power ($q \gtrsim 10^8$ W/cm^2), the stage of erosion plasma formation becomes so short [6, 7] that the process occurs similarly to a low-threshold air breakdown [8]. Such a laser-induced surface air breakdown results in a local plasma formation which almost completely absorbs the acting laser radiation and is a source of intense optical radiation, shock waves, and acoustic disturbances. Therefore, laser-induced surface air breakdown is an attractive object for investigation of different explosion processes under laboratory conditions [9].

The dynamics of shock waves initiated in the case of laser action on different absorbing targets in gases has been investigated in a number of works [10–13], where the trajectory of motion of a shock wave has been investigated by high-speed photographic, shadow, and interferometric methods and by the method of deflection of a probe beam. The authors note the proximity of the experimental trajectories of such shock waves to the Sedov solution [14], especially at low pressures of the gas. At the same time, it is noted [11–13] that the experimental values of the time of arrival of a shock wave at small distances from the breakdown regions are much lower than the expected values for an ideal spherical explosion wave.

Unlike the cited works, in the present work we have measured experimentally two independent parameters: the time of arrival of a shock wave and the pressure at its front. The data obtained were compared to numerical calculations taking into account counterpressure. The measured values of the pressure amplitude at the shock-wave front were compared to the Sedov solution and to the values calculated from the Sadovskii formula [15]. The experimental measurements and the numerical calculations of the indicated parameters were performed for different distances from the breakdown region and different values of the energy of laser-radiation pulses initiating surface air breakdown.

Experimental Setup and Investigation Methods. Laser-induced surface air breakdown at atmospheric pressure was used as the source of shock waves. The breakdown was initiated by pulse laser radiation acting on the end of a metal spoke. In the experiments, we used a setup created based on a pulse-periodic Q-switched YAG:Nd^{3+} laser [16]. The laser pulse (wavelength 1.064 μm) was bell-shaped and its duration was $2 \cdot 10^{-8}$ sec. The laser radiation was focused on the target surface by a plano-convex spherical lens with a focal distance of 60 mm. The diameter of a homogeneous irradiation spot was 200 μm. The laser-pulse energy was changed from 0.8 to 180 mJ using tinted glasses. This corresponded to the range of laser-radiation energy densities 2.5–570 J/cm^2 and power densities 0.1–28 GW/cm^2.

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To record shock waves and acoustic signals we used a piezoelectric transducer of pulsed pressure in the "voltage generator" mode. The structure of the transducer ensured an attenuation of one to two orders of magnitude in the signal of the interference which was caused by the return of elastic waves reflected from the free end of an acoustic waveguide. This enabled us to carry out correct measurements of pressure pulses during time intervals to several milliseconds. The transducer was calibrated by the impact of a steel sphere according to the procedure of [17]. The sensitivity of the transducer was $\sim 7.7 \cdot 10^5$ Pa/V; the measurement error was no higher than 20%. The signals from the pressure transducer were recorded by a BORDO 20.2 digital oscilloscope with an input resistance of 1 MΩ and a discretization frequency of 20 MHz (manufactured by the Belarusian State University, Minsk). The oscilloscope was locked by the external signal from a photodiode recording laser radiation, which enabled us to determine the time of arrival of a shock wave to the transducer.

The dynamics of surface optical breakdown under such conditions has been described in [18] in detail. A laser-supported detonation wave virtually completely shielding the target from laser radiation is formed in the case where the density of the laser-radiation power is $q > 0.3\ \text{GW/cm}^2$. As the density of the laser-radiation power increases to 1 GW/cm^2, radiation processes that become predominant for $q > 4\ \text{GW/cm}^2$ whatever the target material is begin to play an important role in the dynamics of the plasma front. Under such conditions, the plasma front keeps ahead of the shock wave and the plasma formation takes a shape extended toward laser radiation. However the dimension of the plasma formation does not exceed 2 mm even for $q = 12\ \text{GW/cm}^2$. The two-dimensionality of a gasdynamic expansion becomes increasingly more pronounced with cessation of a laser pulse and separation of the shock wave from the plasma front; one can consider the shock wave to be spherical at distances one order of magnitude larger than the dimension of the plasma formation.

At later stages of surface breakdown, the region occupied by hot air comes vertically to the surface under the action of the buoyancy force, which breaks spherical symmetry and limits the possibilities of modeling of unsteady motions using a one-dimensional calculation. The evaluations show that such displacement is 3 to 4 orders of magnitude smaller than the distance covered by the shock wave in this period; therefore, its motion can be disregarded in these experiments.

We have considered several versions of the problem of explosion on the basis of Euler equations with the same boundary conditions and different initial energies whose values were selected in the interval from 0.8 to 180 mJ. All the versions were considered in a spherically symmetric formulation in Lagrangian physical coordinates, which made it possible to track not only the motion of the shock-wave front but also the development of the boundary of the region of energy release. To solve the problem we used a numerical method of direct counting with artificial viscosity [19]; this method is based on a totally conservative difference scheme approximating gasdynamic equations of second order of accuracy in radius and time. Such schemes allow algebraic transformations relating a divergent difference energy equation to a nondivergent equation and thus reproduce the basic property of the initial system of differential equations, i.e., mutual consistency of the laws of conservation of mass, momentum, and energy [20]. This is their important advantage, ensuring the high quality of numerical modeling. The numerical method used is implemented in the form of a software package [21] which enables one to investigate unsteady explosive motions in different media.

The region of gas breakdown was modeled by a spherical energy source of instantaneous action with a radius of $0.1 \cdot 10^{-3}$ m equal to the radius of the irradiation spot. At the initial instant of time $t = 0$, the energy in it was selected to be equal to the laser-pulse energy. The gas density was considered to be equal to the density ρ_0 under normal conditions, while the gas was considered as an ideal gas with $\gamma = 1.4$. The pressure in an undisturbed medium was taken to be $P_0 = 10^5$ Pa. Radiant heat transfer was disregarded in the calculations.

Results of the Experiments and Numerical Calculations. We obtained the oscillograms of pressure pulses at distances of 2–150 mm from the region of laser-induced surface air breakdown in the interval of laser-pulse energies from 0.8 to 180 mJ. Using these oscillograms we determined the values of the pressure amplitude and the time of arrival of a shock wave at reference points and constructed the corresponding dependences on the laser-pulse energy and the distance to the breakdown region. The most detailed measurements were carried out at a distance of 5, 10, and 20 mm from the breakdown region.

The experimental values of the pressure amplitude of a shock wave as functions of the distance to the breakdown region for a constant energy of laser pulses of 75 mJ are given in Fig. 1 (points 1). The dependence of the

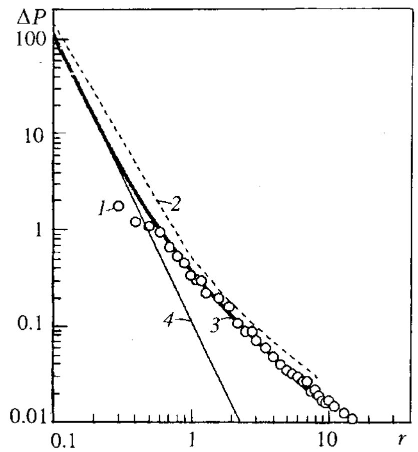

Fig. 1. Amplitude of the shock wave vs. distance to the region of the laser-induced surface air breakdown: 1) experimental data; 2) Sadovskii formula; 3) numerical calculation; 4) Sedov self-similar solution. ΔP, bar; r, cm.

pressure amplitude on the distance 2 calculated in accordance with the Sadovskii semiempirical formula and the dependence 3 obtained by numerical calculation are given in the same figure. Furthermore, Fig. 1 gives the results (shown by curve 4) of the self-similar solution of Sadovskii. It is seen from the figure that the experimental data are in qualitative agreement with the results of numerical calculations over the entire region of measurements. Quantitative agreement is observed beyond the region of radius 5–6 mm, whereas near the breakdown region the experimental data lie much lower than the calculated dependence. As the distance to the breakdown region decreases, the results of the numerical calculations become increasingly closer to the self-similar solution. The self-similar solution only intersects the experimental curve near the breakdown region.

The Sadovskii formula yields a dependence which is in qualitative agreement with the results of the numerical calculation but runs somewhat higher than the latter (Fig. 1, curves 2 and 3). This semiempirical formula was obtained from comparison of the numerical results to the data of experiments on large-scale explosions [15]. The agreement between the results of our calculations and this formula demonstrates the correctness of the computational algorithms used and their software implementation; it also shows that one can correctly calculate the problems of large-scale explosions with counterpressure in a one-dimensional formulation using a software package [21]. The distinctions between the experimental pressure amplitudes of a shock wave and the amplitudes computed from the Sadovskii formula (points 1 and curve 2) which are seen in Fig. 1 can indicate a significant difference between a microexplosion and a large-scale explosion.

Near the region of the air breakdown, the experimental dependence of the pressure amplitude of a shock wave on the distance differs from the calculated curve in slope and position (Fig. 1). In this region, it also differs from the self-similar solution of Sedov and from the computations according to the Sadovskii formula. The distinctions observed here can be explained by the influence of the dissipation caused by radiant heat transfer, heat conduction, and internal friction. However in the numerical calculation which is based on gasdynamic Euler equations, the indicated processes are disregarded. Therefore, it should be natural to expect a slower attenuation of the calculated shock wave as compared to the actual one. But the experiment has shown that the amplitude of the actual shock wave is attenuated much more slowly than the amplitude of the calculated shock wave near the breakdown region.

It follows from what has been stated above that the actual picture of development of unsteady explosive motions near the breakdown region differs significantly from the picture given by a gasdynamic description. The weaker attenuation of the shock wave can be caused by the fact that under actual conditions the smaller mass of the air than follows from the gasdynamic equations is involved in unsteady explosive motion on this portion. With distance from the site of explosion the mass involved in motion relatively increases and the attenuation of the actual amplitude becomes closer to the attenuation of the calculated amplitude. Therefore, at relatively large distances from the breakdown region (10 and 20 mm), the experimental values of the pressure amplitude in the shock wave are in good agreement

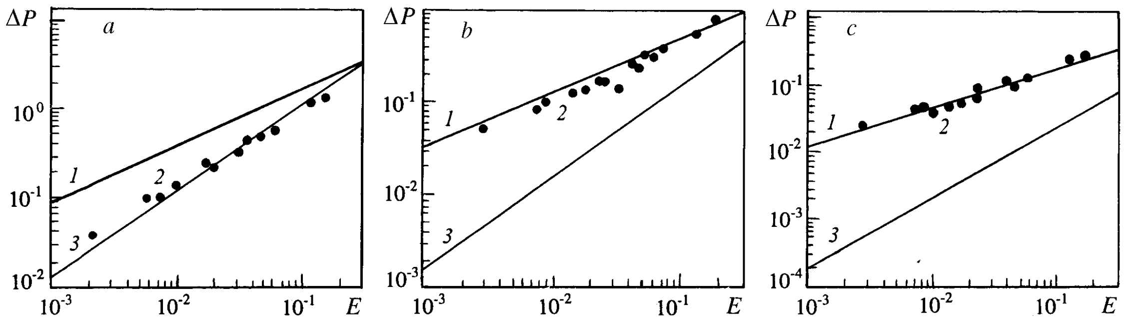

Fig. 2. Amplitude of the shock wave vs. laser-pulse energy at a distance of 5 (a), 10 (b), and 20 (c) mm from the breakdown region: 1) numerical calculation; 2) self-similar solution. ΔP, bar; E. J.

with the results of numerical calculation. Thus, the actual explosive expansion markedly differs from the model one in transport properties.

The results of experimental measurements of the pressure amplitude of a shock wave at fixed distances of 5, 10, and 20 mm from the region of optical air breakdown as a function of the laser-pulse energy are given in Fig. 2. This figure also gives the results of numerical calculations (curve 1) and the Sedov self-similar solution (curve 3). It is seen that all the mentioned dependences are in qualitative agreement in the region of measurements performed.

Quantitative agreement between the experimental and calculated data is observed at rather large distances (10 and 20 mm) from the breakdown region (Fig. 2b and c). At a distance of 5 mm, this agreement becomes poorer. Here the calculated amplitudes of pressure in the shock wave are appreciably higher than the experimental amplitudes (Fig. 2a). This is, apparently, caused by the radiation loss, which can be rather significant at the stage of existence of the dense plasma formation but has been disregarded in the calculations.

A surprising agreement between the experimental values of the pressure amplitudes and the self-similar solution is revealed at a distance of 5 mm from the breakdown region throughout the range of the investigated laser-pulse energies (Fig. 2a) despite the fact that this solution takes into account neither radiant transfer nor counterpressure. Such agreement can be explained by the fact that radiant transfer and counterpressure exert an opposite influence on the dynamics of unsteady explosive motions. As is seen, both effects are mutually counterbalanced at a distance of ~5 mm from the breakdown region. The dependence of the pressure amplitude in the shock wave on the radius that corresponds to the self-similar solution intersects the experimental curve in such a manner that in the case of smaller distances from the breakdown region where the influence of the radiant transfer is large and the counterpressure can be disregarded the self-similar solution yields values of the amplitudes much higher than the experimental ones (Fig. 2). In the case of larger distances from the breakdown where the radiant transfer is weak and the influence of the counterpressure is large, the self-similar solution runs much lower than the experimental values.

It should be noted that the results of the numerical calculations and the experimental data are approximated well by the power-law dependences on energy while the Sedov solution yields the linear dependence of the pressure amplitude on the energy. The exponent decreases as the distance between the reference point and the breakdown region increases. In particular, at distances of 5, 10, and 20 mm, the exponent is equal to 0.65, 0.574, and 0.546 respectively. However near the breakdown region the calculated curve deviates somewhat from the power-law dependence even at $r = 5$ mm (Fig. 2a). This can be explained by the influence of the finite size of the energy source and of the pressure jumps generated by the source and catching up with the Mach primary front and merging with it.

The results of measurements of the time of arrival of a shock wave at distances of 5, 10, and 20 mm from the breakdown region are presented in Fig. 3. Here the experimental data are denoted as points while the calculated dependences are shown as curves (1, 2, and 3 respectively). It is seen that the experimental dependences are in qualitative agreement with the calculated dependences throughout the region of investigated energies. However the measured values of the time of arrival of the shock wave decrease more slowly than the calculated values with increase in the laser-pulse energy at all the reference points. In particular, at a distance of 5 mm from the breakdown region the experimental times of arrival of the shock wave are in good agreement with the calculated values for low energies of laser pulses. But with increase in the laser-pulse energies the agreement between the results becomes poorer in such a

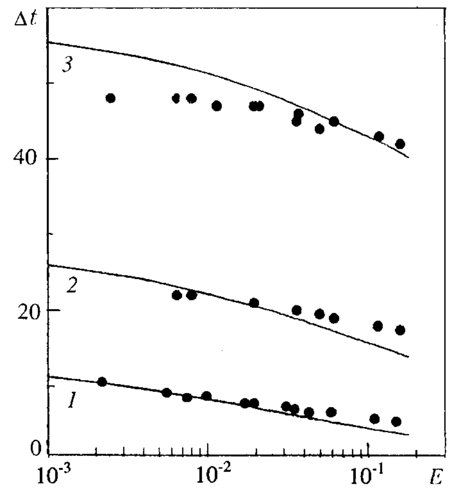

Fig. 3. Time of arrival of the shock wave vs. laser-pulse energy at a distance of 5(1), 10 (2), and 20 (3) mm from the breakdown region: points, experiment; curves, calculation. Δt, μsec; E, J.

manner that for higher energies of the breakdown the actual shock wave propagates more slowly than the calculated one.

Near the breakdown region, the measured values of the pressure amplitudes are appreciably lower than the calculated values (see Figs. 1 and 2a) most probably because of the radiation loss which has been disregarded in the calculations. However, in addition to the attenuation of a shock wave, the radiant transfer causes the heating of the air ahead of the shock-wave front, which ensures a higher velocity of propagation of the shock wave and a reduction in the time of its arrival at a given distance. This can explain the coincidence of the measured and calculated values of the time of arrival of the shock wave for low energies of the breakdown despite the distinction between the calculated and measured amplitudes of pressure (Fig. 2a). However for high energies of the breakdown the influence of the radiation loss on the velocity of propagation of the shock wave is, apparently, no longer compensated for with the radiant heating of the air ahead of the shock-wave front.

At a distance of 10 mm from the breakdown region, the agreement between the experimental and calculated values of the time of arrival of the shock wave is much poorer despite the agreement between the measured and calculated amplitudes of pressure (see Fig. 2b). In this case, for low energies of the breakdown the actual shock wave propagates more rapidly than the calculated shock wave while for low energies it propagates more slowly (Fig. 3, curve 2).

Such a feature is characteristic of a distance of 20 mm from the breakdown region. Here the experimental values of the time of arrival of the shock wave are appreciably lower than the calculated values for low energies and approach them with increase in the laser-radiant energy (Fig. 3, curve 3). In other words, for low energies of the breakdown and a large distance from it the actual shock wave propagates much more rapidly than the calculated shock wave. This demonstrates that in the calculation we have failed to take into account a certain significant physical process which ensures the smaller degree of involvement of the air mass in unsteady explosive motion than the calculated one. This process is related neither to the transfer of heat nor to internal friction and, possibly, is inhibited by them, since it is pronounced in the middle and far zones of the explosion when the influence of these processes becomes much weaker with decrease in the intensity of the motions. Such a process could be the transformation of the shock-wave motion behind the shock-wave front to an acoustic disturbance which, as is well known, is not accompanied by the transfer of mass.

The assumption of the instability of shock-wave motion because of acoustic dispersion and of the excitation of acoustic vibrations has been proposed in [9] to explain the discrepancy between the measured and calculated recoil momentum under the conditions of a spherical explosion in air. The evaluations based on such an approach point to the relation of the explosion energy to the dominant frequency and the width of the acoustic spectrum. A similar relation of the width of the spectrum of acoustic radiation initiated by the optical air breakdown has been revealed experimentally [22]. Therefore, to elucidate why the distinctions between the experimental and calculated results have been detected it is necessary to investigate acoustic disturbances and the relation of their characteristics to the parameters of an actual explosion.

Thus, we have measured experimentally and calculated numerically the amplitude and time of arrival of a shock wave initiated by the laser-induced surface air breakdown at different distances from the breakdown region versus the energy of laser pulses. Good agreement between the experimental values of the shock-wave amplitude and the one-dimensional calculation at distances of 6 to 100 mm to the breakdown region has been established. This indicates that a model source of shock waves with an amplitude reproducible and controlled well in a wide range can be created under laboratory conditions. The distinction between the experimental and calculated amplitudes near the breakdown region can be caused by a number of factors which necessitate additional investigations.

For the time of arrival of the shock wave we have failed to obtain good agreement with the numerical calculation performed. We observe an appreciable disagreement between the experimental and calculated values of the time of arrival of the shock wave under some conditions and their agreement under others, which is caused by the more mildly sloping experimental dependences on the laser-pulse energies as compared to the calculated dependences. The analysis of the data obtained has shown that for low energies of laser pulses the actual shock wave propagates more rapidly than the calculated one, while for high energies it propagates more slowly.

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NOTATION

q, density of the laser-radiation power; E , laser-pulse energy; r, distance from the center of the laser-induced air breakdown to the observation point; t, time; ρ_0, initial density of the medium (air); γ, adiabatic exponent; P_0, counterpressure; ΔP, pressure amplitude in the shock wave.

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