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FEATURES OF THE TIME SHAPE OF THE PRESSURE PULSES OF OPTICAL AIR BREAKDOWN

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The time shape and amplitude of pressure pulses initiated by surface laser air breakdown for different energies of laser pulses (1–180 mJ) has been compared to the results of numerical gasdynamic calculations of unsteady explosive motions with allowance for counterpressure at distances of 0.2 to 30 cm from the breakdown region. It has been established that the experimental pressure pulse has the character of slowly damped quasiperiodic vibrations, whereas the calculated pulse is a bipolar single pulse of a much shorter duration. Good agreement between the experimental and calculated amplitudes of a positive pressure phase has been found throughout the investigated range, whereas the agreement between the corresponding amplitudes and durations of a negative pressure phase is limited in character. The differences observed in the experimental and calculated data have been attributed to the transformation of the shock-wave motion to acoustic radiation.

The action of pulsed laser radiation in metal targets in air for fairly high power densities ($q \geq 10^8$ W/cm^2) generates a surface-plasma formation absorbing the laser radiation almost completely. Such a local plasma formation is a source of intense optical radiation and explosive gasdynamic and acoustic disturbances. Therefore, the surface laser air breakdown represents a convenient object for investigating explosion physics under laboratory conditions [1].

The dynamics of shock waves initiated by laser action on absorbing targets in gases has been investigated in a number of works [2–5]. In them, the trajectories of motion of the shock-wave front has been determined experimentally and has been compared to different analytical and numerical models. It was shown that, as the energy contribution of laser radiation to the surface laser plasma increases, the trajectories of the shock waves approach those calculated according to the self-similar solution of Sedov [6]. The recent investigations of the authors [7] have shown that the agreement between the experimental amplitudes of the shock waves and the Sedov solution is observed just in a certain vicinity of the optical breakdown, whereas at a large distance from it the experiment is in agreement with numerical calculation with allowance for counter pressure and with the approximation formula of Sadovskii.

In the present work, we have investigated experimentally the characteristics of the of pressure pulses at different distances from the region of surface optical breakdown and for different values of the laser-pulse energy. We have also studied the amplitudes of pressure on the shock-wave front and the period of existence of the positive and negative pressure phases as functions of the distance traversed by the shock wave. The data obtained have been compared to the results of numerical calculations performed with allowance for counterpressure.

Experimental Setup and Investigation Methods. A surface laser atmospheric-pressure air breakdown was used as the source of shock waves. The breakdown was initiated by the pulsed laser radiation acting on the end of a metal spoke. In the experiments, we employed a setup created on the basis of a Q-switched pulse-periodic YAG:Nd^{3+} laser [8]. 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 length of 60 mm. 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 of 2.5–570 J/cm^2 and power densities of 0.1–28 GW/cm^2.

To record UV and acoustic signals we employed a piezoelectric pulsed-pressure transducer in the "voltage generator" regime. The design of the transducer ensured an attenuation of one to two orders of magnitude in the am-

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plitude of 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 correctly measure pressure pulses over intervals of several milliseconds. The transducer was calibrated by the impact of a steel sphere according to the procedure of [9]. The transducer sensitivity was $\sim 7.7 \cdot 10^5$ Pa/V; the measurement error for the amplitude was no higher than 20%. The signals from the pressure transducer were recorded by a BORDO 20.2 digital oscilloscope (manufactured by the Belarusian State University, Minsk) with an input resistance of 1 MΩ and a discretization frequency of 20 MHz. The oscilloscope was synchronized by the external signal from the photodiode recording laser radiation, which also enabled us to determine the time of arrival of a shock wave at the transducer.

The dynamics of surface optical breakdown under such conditions has been described in [10] in detail. When the density of the laser-radiation power is $q > 0.3$ GW/cm^2, a light-detonation wave is formed, which virtually completely shields the target from laser radiation. As the laser-radiation-power density increases to 1 GW/cm^2, radiation processes begin to be of considerable importance in the dynamics of the plasma front; these processes become dominant for $q > 4$ GW/cm^2 whatever the target material. Under these conditions, the plasma front keeps ahead of the shock wave and the plasma formation acquires a shape extended toward laser radiation. However, the dimensions of the plasma formation are no larger than 2 mm, even for q = 12 GW/cm^2. With cessation of the laser pulse and separation of the shock wave from the plasma front, the two-dimensionality of the gasdynamic spreading is increasingly less pronounced, and at a distance an order of magnitude larger than the dimension of the plasma formation one can assume the shock wave to be spherical with a high degree of accuracy.

Unsteady motions caused by the optical breakdown were numerically modeled by solving the discontinuity disintegration problem that was posed as the Cauchy problem for the system of Euler equations of gas dynamics. We have considered several variants of this problem with identical boundary conditions and different initial energies whose values were selected in the interval from 0.8 to 180 mJ. All the variants were considered in a spherically symmetric formulation in Lagrangian physical coordinates, which makes it possible to track not only the motion of the shock-wave front but also the development of the boundary of the energy-release region. For solution we employed the numerical method of through counting with artificial viscosity [11]. A similar problem had already been solved by such a method in [12] with the use of a divergent difference scheme. More perfect difference schemes called totally conservative schemes were developed at a later time [13]. Such schemes allow algebraic transformations relating a divergent difference equation to a nondivergent equation, and in so doing they reproduce the main property of the initial system of differential equations, i.e., mutual consistency of the laws of conservation of mass, momentum, and energy. We employed a similar difference scheme to obtain numerical solutions. The adopted approach has been implemented in the form of a software package [14] which enables one to investigate unsteady explosive motions in different media.

A highly heated isothermal sphere whose expansion generates shock-wave motion was considered as the energy source. At the initial instant of time t = 0, the radius of the sphere was taken to be equal to the radius of the irradiation spot ($0.1 \cdot 10^{-3}$ m). The energy of the sphere was selected to be equal to the energy of the laser pulse. The density of the gas inside the sphere and outside it was assumed to be equal to the density of air under normal conditions. In what follows, we will call this region the explosion source. The counterpressure P_0 was taken to be equal to the air pressure under normal conditions. The gas was described as an ideal one with γ = 1.4.

Thus, the calculations are based on the assumption of instantaneous energy release, whereas in the experiments the laser-radiation energy is absorbed in the plasma throughout the duration of the pulse (~20 nsec). Therefore, the selected initial conditions of calculation lead to overstated initial plasma temperatures which are much higher than their values in the actual surface laser air breakdown. In this connection, we also carried out calculations with other initial conditions where the initial dimensions of the explosion source were selected to be obviously larger than the radius of the irradiation spot so as to fit the initial temperature in the experiment to that in the calculation. It was revealed that the results of both variants of calculation differ insignificantly beyond a certain region in the vicinity of the explosion source, which is attributable to the neglect of radiant heat conduction in the calculation carried out. Therefore, subsequent calculations were carried out with normalization to the dimensions of the irradiation spot, which ensured the construction of a computational grid fairly narrow for detailed representation of unsteady motions.

Results of the Numerical Calculations and Experiments. The calculations yielded a complex pattern of development of unsteady motions, which is qualitatively identical for all the variants. Behind the shock-wave front, there

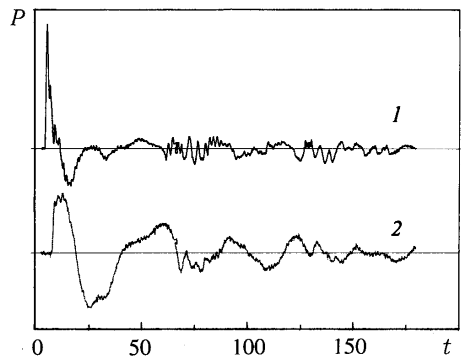

Fig. 1. Normalized oscillograms of a pressure pulse in the vicinity of a surface laser air breakdown (1) and at a distance from it (2): 1) r = 0.5; 2) 30 cm (E = 75 mJ). P, rel. units; t, μsec.

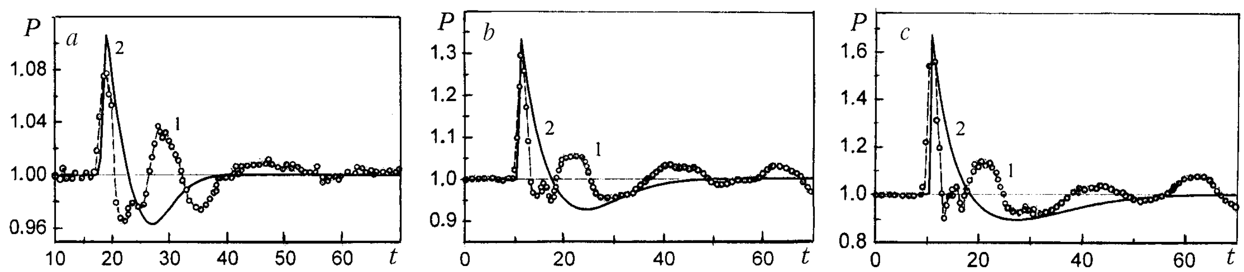

Fig. 2. Experimental (1) and calculated (2) shapes of a pressure pulse for different energies of the laser pulse initiating a surface air breakdown: a) 7; b) 60; c) 180 mJ (r = 1 cm). P, bar; t, μsec.

is a region (covering the center of the explosion source) of low values of the pressure and density. In the near explosion zone, the pressure and density in this region are higher than their values in an undisturbed medium. In the explosion source, we have fluctuations of the mass velocity in value and direction, which are accompanied by the generation of repeated shocks catching up with the main front and merging with it. This process ensures additional removal of energy from the explosion source to the environment.

The emergence of the shock-wave front in the central zone of the explosion is accompanied by cessation of the generation of repeated shocks. The explosion-source radius attains its maximum and then somewhat decreases. A region of return flow in which a negative mass-velocity profile is established is formed around the center; the pressure and density in this region are much lower than their values in the undisturbed medium.

Finally, with the emergence of the shock-wave front in the far zone of the explosion, a region of rest is formed whose boundary extends with the velocity of sound. The pressure in the region of rest coincides with P_0, while the mass velocity is equal to zero. When its boundary goes beyond the explosion source, the dimensions of the source are stabilized and it ceases to influence motion. Thereafter the energy of the explosion source remains constant. The behavior of the amplitude parameters of disturbance reaches the asymptotics of a point explosion [1]. The shock-wave peak acquires the shape of a wide region of increased pressure. Between it and the region of rest, there extends the zone of return flow in which the mass velocity is directed to the center and the pressure is lower than P_0. Thereafter the pattern of motion does not substantially change and the disturbance propagates in the form of a bipolar pressure pulse of decreasing amplitude. A similar pattern of development of unsteady motions is yielded by all the existing numerical calculations of a spherical explosion with counterpressure. However, we obtained pressure pulses with a more complex shape in the experiments (Fig. 1). In them, the head shock-wave peak and the short-duration negative pressure phase are followed by quasiperiodic pulsations of a much smaller amplitude. It has been found that with increase in the distance such pressure pulsations decay much more slowly than the peak amplitude. A marked broadening of the shock-wave peak is found with distance from the breakdown region (Fig. 1). No region of rest was revealed throughout the investigated range of divergence times up to 3 msec.

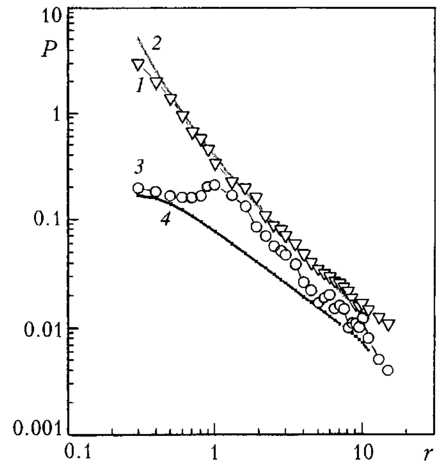

Fig. 3. Experimental and calculated amplitudes of a shock wave (1, 2) and a negative pressure phase (3, 4) as functions of the distance to the region of laser surface air breakdown (E = 75 mJ). P, bar; r, cm.

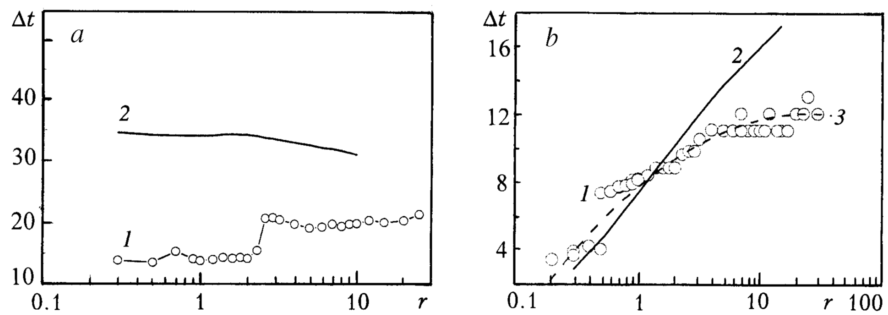

Fig. 4. Experimental (1) and calculated (2) durations of the negative pressure phase (a) and the shock-wave peak (b) as functions of the distance to the region of laser surface air breakdown; 3) approximation polynomial (E = 75 mJ). Δt, μsec; r, cm.

We obtained a great deal of pressure oscillograms for different laser-pulse energies from 1 to 180 mJ. It has been found that, as the energy of the laser pulses increases, the amplitude of the shock-wave peak increases much more rapidly then the amplitude of subsequent pulsations (Fig. 2). A comparative analysis of the numerous experimental and calculated pressure pulses has revealed their agreement in the amplitude of a shock-wave peak (Figs. 2 and 3). We note that the experimental and calculated pulses were brought into coincidence by the position of the maximum for the convenience of comparison, despite some difference in the time of arrival of the actual and calculated shock waves [7]. The shock-wave peak (see Fig. 2) is followed by a low-pressure region whose characteristics markedly differ even in the experimental and calculated pulses. New peaks of pressure with a decreasing amplitude are disclosed in the experiment at subsequent instants of time, whereas numerical calculation yields the pressure reaching a plateau. For the convenience of analyzing the shape of pressure pulses, we plotted the experimental and calculated duration of the negative pressure phase (Fig. 4a) and the corresponding durations of the shock-wave peak (Fig. 4b) against the distance to the region of laser surface air breakdown.

Despite the revealed differences in the actual and calculated shapes of pressure pulses, their shock-wave-front amplitudes are in good agreement. This has been confirmed in a rather wide range of laser-pulse energies (Fig. 2) and distances from the region of optical breakdown (Fig. 3). At the same time, no similar agreement is observed for the negative phase of pressure. Thus, the experimental dependence of the amplitude of the negative pressure phase on the distance has ascending and descending branches with the maximum at $r \approx 1$ cm (Fig. 3, curve 3). The calculated dependence (Fig. 3, curve 4), conversely, is characterized by a monotone decrease with increase in the distance and, in the central part, it lies much lower than the experimental dependence. However, both dependences are in agreement in the vicinity of the breakdown region and at a large distance from it.

The experimental duration of the negative pressure phase depends on the distance as a step function (Fig. 4a, curve 1). At the same time, the calculated duration (Fig. 4a, curve 2) is much longer than the measured duration and it monotonically decreases with distance. The tendency of the calculated profile toward reversing and forming a shock wave in the region of lowered pressure manifests itself as such a decrease. This feature of an explosion with counterpressure was predicted in [15] and was confirmed for the first time by a numerical calculation whose results have been given in [16]. However, experiment does not reveal such a tendency. Conversely, the experimental duration, as is clear from Fig. 4a, increases abruptly for $r \approx 2\lambda$. Here we have $\lambda = (E/P_0)^{1/3}$.

The experimental dependence of the duration of the head peak of disturbance on the distance (Fig. 4b) is characterized by several discontinuities between which there are portions of slow growth and by reaching the plateau. The calculated dependence increases monotonically, in much the same manner as the logarithm of distance. At small distances from the breakdown, the calculated duration is shorter than the measured duration and their values are fairly close. At large distances, conversely, the calculated duration is substantially longer than the measured duration.

In the actual medium, the nonlinear effects counteract the dissipative effects. Whereas the former lead to a narrowing of the shock-wave peak, the latter cause it to broaden. The shape of the actual peak is determined by their joint action [17]. However, the Euler equation disregards dissipation. Therefore, the increase in the calculated width and accordingly duration of the shock-wave peak of pressure is caused by the decrease in the nonlinearity as the amplitude of the shock-wave front decreases. One should expect an advanced increase in the actual duration of the positive pressure phase as compared to the calculated duration because of the dissipative effects. However, this does not occur. The measurements reveal the opposite: the actual duration of the shock-wave peak on the portions between discontinuities increases more slowly than the calculated duration. Such a dependence points to some other physical processes that counteract dissipation and cause the discontinuities of the experimental dependence and reaching of the plateau by it. These processes, apparently, are not associated with the nonlinear effects and are, possibly, suppressed by them since they manifest themselves with significant decrease in the shock-wave amplitude when the influence of such effects becomes small. Thus, the employed numerical model of an explosion with counterpressure is not complete since it disregards the processes causing the difference in experimental and calculation results.

Possible Mechanism of Generation of Vibrations. The generation of acoustic vibrations in the process of laser action is attributable to the evaporation of the target material. However, under the realized conditions of laser surface air breakdown, the contribution of the evaporative mechanism of generation of the vibrations is insignificant. This has been confirmed by our experiments with optical air breakdown without a target. The oscillograms of pressure pulses, obtained under such conditions and in the case of an optical discharge in the vicinity of the target surface, were no different, in practice. This demonstrates the negligibly small contribution of the evaporative mechanism to the generation of acoustic air vibrations under our experimental conditions.

The shadow investigations (performed in [18]) of the hydrodynamic relaxation of a hot zone after the optical air breakdown demonstrate a complex three-dimensional dynamics of disturbances of the gas density. As Bufetov et al. believe, under the conditions of a pronounced asymmetry of the region of optical discharge propagating along the laser beam, there are developing hydrodynamic instabilities caused by the formation of a cumulative cold-gas jet and vortex disturbances. Instabilities of this kind can lead to pressure pulsations which must be random in character. These instabilities are developing in the region of optical breakdown and they cannot exert a substantial influence on the motion and shape of the head peak of disturbances.

It should be said that in our experiments we did not have a pronounced asymmetry of the optical discharge owing to the short duration of the laser pulse and the employment of a short-focus lens. Moreover, a number of facts demonstrate the proximity of the symmetry of gasdynamic motions realized under such conditions to a spherical one. This is supported by the agreement of the experimental amplitudes and the durations of the positive phase of a breakdown-initiated pressure pulse with the results of numerical modeling in a spherically symmetric statement. Under these conditions, we observe quasiperiodic pressure pulsations which are difficult to relate to the hydrodynamic instabilities described in [18].

As we believe, the excitation of pressure oscillations under the conditions in question can be caused by another mechanism which is due to the specific decay of the shock-wave peak. Let us consider the processes occurring in this case in greater detail. At a later stage of the optical breakdown, the laser plasma becomes a hot volume of low-density air whose intrinsic motions are damped. When the shock-wave front is at a sufficiently large distance, the zone of return flow is formed. The Mach numbers in the vicinity of the zone boundary with a head peak differ little from zero. Under these conditions, the effects of acoustic dispersion dominate over the nonlinear effects [19]. Therefore, here the shape of the head peak loses its stability and its decay and the emission of waves by the front toward the center begin. By virtue of the law of conservation of momentum, the velocity of the head peak increases and the increase in its duration is retarded as compared to the calculated duration (see Fig. 4b). Such a process of emission of acoustic waves also limits the development of the zone of return flow and prevents the region of rest from appearing at the center. Therefore, the duration of the negative pressure phase is shorter than the calculated duration (Fig. 4a).

Convergent acoustic waves can transform to shock waves in a viscous heat-conducting medium under certain conditions [20]. Such sound waves find themselves in the region with decreasing density and increasing temperature, which favors such a transformation [21]. Therefore, here the convergent acoustic waves transform to shock waves, which are subsequently reflected from the center and remove part of the energy of the explosion source. Thereafter such shock waves catch up with the head pressure peak and merge with it, owing to which its width increases abruptly (Fig. 4b).

Thus, the specific regime of unsteady motions is ensured by the positive feedback of the shock-wave front to the hot region of optical breakdown and has a pronounced threshold character. Its beginning corresponds to the distance between the shock and the center of the breakdown above 0.5λ. The regime is "switched-off" as a consequence of the breaking of the indicated feedback after cessation of the transformation of the convergent acoustic waves to acoustic ones at the instant when the compression waves reflected from the center are unable to catch up with the head peak of pressure because of the dispersion decay of they themselves. The increase in the head-peak width is retarded and reaches a plateau (see Fig. 4b), while the experimental and calculated values of the amplitude of the negative pressure phase become close again (see Fig. 3). The level of this plateau and the shape of the head peak are determined by the joint influence of the dissipation and the processes of dispersion decay of the head peak. The process of transformation of a shock-wave disturbance to an acoustic-radiation pulse is completed with cessation of such a regime.

The results obtained in the present work enable us to draw the following conclusions:

1. The experimental pressure pulse has the character of damping quasiperiodic vibrations, whereas the calculated pulse represents a bipolar single pulse of a much shorter duration.

2. The experimental and calculated amplitudes of the head shock peak are in good agreement throughout the investigated range of distances to the breakdown (0.5–30 cm), whereas the amplitude of the negative pressure phase is in agreement with calculation only in the vicinity of the breakdown and at large distances from it.

3. The duration of the head peak is in agreement with calculation predominantly in the vicinity of the breakdown region, and the duration of the negative pressure phase significantly differs from calculation throughout the investigated range of distances.

4. The difference in the experimental and calculated results is attributable to the dispersion decay of the shock-wave peak, ensuring the generation of convergent acoustic waves and their transformation to shock waves with subsequent reflection from the center of the breakdown region.

NOTATION

q, density of the laser-radiation power, W/cm^2; t, time, μsec; γ, adiabatic exponent; P_0, counterpressure; Δt, duration of the head peak of the disturbance and of the negative pressure phase, μsec; P, pressure in the units of P_0; r, distance from the center of the breakdown, cm; λ, dynamic breakdown length; E, laser-pulse energy.

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