Comparison of initial pressure distributions in shock wave simulation of optical breakdown on surface

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Abstract. In this work we investigated the velocity of propagation of a shock wave after optical breakdown on the surface, depending on various initial pressure distributions which are simulated in Ansys Fluent. When setting of the shock wave energy of the order of 10...20% of the laser pulse energy, results are in satisfactory agreement with experiments. An analysis of the experimental data showed an effect when the velocities of shock waves propagation are comparable but energies of laser pulses differ by two orders of magnitude between each other, which leads to significant deviations from the theory of a point explosion

Keywords: Numerical simulation, optical breakdown, shock wave, theory of point explosion

1. Introduction
Some practical problems, such as hardening materials or developing a laser rocket engine, require the estimation of the parameters of the shock wave on the surface of the material. In addition to conducting experiments, it is possible to use numerical modeling, which allows to visualize gas flows and assessing the pressure and velocity of the gas over time.
The description of the development of an optical breakdown shock wave inside the channels is relevant for spheres that use the energy of a laser pulse for interaction with other materials, for example, material hardening or a laser rocket engine.
Various initial pressure distributions can be used to simulate the development of a shock wave. Purpose of this work is to investigate the influence of pressure distributions, such as linear and according to the Sedov’s theory of point explosion, on the pressure and motion of the shock front.

2. Model description
Based on the experimental work, the following stages of the development of a shock wave on the surface can be distinguished [1-4].
Figure 1. Diagram of the development of a shock wave during optical breakdown
1 – moment of time $t_{\infty}$, the external environment is not disturbed, the parameters of the environment are constant; 2 – moment of time $t_0$, at this moment, an optical breakdown occurs near the surface, the propagation of a hemispherical shock wave begins; 3 – moment of time $t_1$, the shock wave stops to be self-similar and continues to propagate; 4 – moment of time $t_2$, the shock wave downgrades into a sound wave, pressure on the shock wave slightly more than ambient pressure.

For the numerical calculation input parameters are required. In this case, it is possible to apply the Sedov theory to estimate the parameters of the gas after the explosion [5-6]. Theory has formulas to calculate gas pressure behind the shock front $p_2$, gas velocity behind the shock front $V_2$, speed of the shock wave propagation $D$ and coordinate of a spherical shock wave $r_2$. During the analysis, it was determined that the discharge is a spherical explosion, i.e. $\nu = 3$.

The gas pressure behind the shock front is

$$p_2 = 21.1 \cdot p_1$$  \hspace{1cm} (1)

where $p_1$ – pressure of the external environment

The coordinate of a spherical shock wave is determined

$$r_2 = l \cdot r^0$$  \hspace{1cm} (2)

where $l$ – dimensionless shock wave coordinate, $r^0$ – dynamic characteristic length, which is defined as

$$r^0 = \left( \frac{E_0}{p_1} \right)^{\frac{1}{3\nu}}$$  \hspace{1cm} (3)

where $E_0$ – explosion energy, $\nu$ – parameter, for the spherical case equal to 3.

The gas velocity behind the shock front is defined as

$$V_2 = \frac{2 \cdot a}{\gamma + 1} \cdot (1 - q) \cdot q^{-\frac{1}{2}}$$  \hspace{1cm} (4)

where $q = \frac{a^2}{D^2}$; $a$ - speed of sound in an unperturbed external environment; $D$ – speed of the shock wave propagation is defined as

$$D = 0.4 \left( \frac{E}{\rho_1} \right)^{\frac{1}{2}} \cdot r_2^{\frac{3}{2}}$$  \hspace{1cm} (5)
where $\rho_1$ – density of the undisturbed external environment (in this case, air); $E$ – this is a quantity that has the same dimension as the shock wave energy released during the explosion $E_0$, is defined as

$$E_0 = 1.175 \cdot E$$  \hspace{1cm} (6)

The simulation is started from the moment of time $t_1$, when the difference between the ambient pressure and the pressure on the shock wave is 21.1 times. This moment in time is taken due to the loss of self-similarity, i.e. environmental conditions influence on shock wave motion. Ansys Fluent 17.2 software was used for numerical simulation. It is used 2D problem statement, field length 0.02 m, field height 0.015 m, density-based solver, transient time. Output condition is pressure-outlet with permeable walls and pressure of 101325 Pa at infinity. An inviscid fluid model was used for calculation, air was chosen as an ideal gas. Ambient pressure is 101325 Pa, temperature is 293 K. Initial coordinate of a spherical shock wave $r_2$ is 0.001285 m, gas pressure behind shock front is 2.14 MPa. Gas velocity behind shock front equals to 1010 m/s using (4), distribution is linear.

![Figure 2. Left - Velocity distribution according to Sedov and in the model, where ■ is the distribution according to model, ● is the distribution according to Sedov. Right - pressure distribution graphs which used for calculations, where ■ is the pressure distribution according to Sedov, ▲ is pressure distribution similar to density distribution according to Sedov, ● is linear distribution](image)

It was used 3 types of pressure distributions for modeling - linear, pressure distribution according to Sedov theory and distribution similar to density distribution. Equation (7) allows to set pressure distribution according to Sedov theory. As you can see from Figure 2 there is a so-called "pressure plateau", where static pressure is about 35% of the pressure at shock front. Using an approximation, it was determined that the equation, which describing initial pressure distribution according to Sedov theory at a coordinate $r_2 = 0.001285$ m, equals

$$p_2 = 1.23 \cdot 10^{32} \cdot r^8 - 5.72 \cdot 10^{29} \cdot r^7 + 1.09 \cdot 10^{27} \cdot r^6 - 1.09 \cdot 10^{24} \cdot r^5 + 6.13 \cdot 10^{20} \cdot r^4 - 1.90 \cdot 10^{17} \cdot r^3 + 2.95 \cdot 10^{13} \cdot r^2 - 1.71 \cdot 10^9 \cdot r + 781729$$  \hspace{1cm} (7)

and pressure distribution, similar to density distribution for the same coordinate, is

$$p_2 = 2.146 \cdot 10^{32} \cdot r^8 - 9.942 \cdot 10^{29} \cdot r^7 + 1.885 \cdot 10^{27} \cdot r^6 - 1.977 \cdot 10^{24} \cdot r^5 + 1.048 \cdot 10^{21} \cdot r^4 - 3.229 \cdot 10^{17} \cdot r^3 + 4.979 \cdot 10^{13} \cdot r^2 - 2.877 \cdot 10^9 \cdot r + 493$$  \hspace{1cm} (8)

where $r = \sqrt{x^2 + y^2}$, $x$ и $y$ are coordinates.
3. Results

Numerical simulation results are presented below.

As seen from Figure 4, parameters of the shock front at the initial pressure distribution, according to Sedov theory, are more accurate than at the initial linear distribution. Selection of the initial distributions according to Sedov theory is difficult. It is possible to use a linear distribution for preliminary calculation.
4. Discussion

There are many experimental works in which a shock wave generated by a pulsed optical breakdown on a flat surface is recorded by a high-speed camera. Different velocities of shock wave propagation are obtained when comparing experimental studies in the same range of laser pulse energies under comparable conditions. It is used to experimental data from [4] to check calculation method. Shock wave energy was set at 10 and 20% of laser pulse energy. Calculation results are presented below.

![Figure 5](image_url)

**Figure 5.** Comparison of experimental and calculated data on surface

The coordinates of the shock front at energies near 10-20% of the laser pulse energy are located rather close, but discrepancy with ideal result increases with time. Simulation results are in satisfactory agreement in comparing with other experimental data with comparable pulse energies.

Experimental curves, for example, at a pulse energy of 3.6 J and 0.045 J, or 4.2 J and 0.13 J, in Figure 5 are enough similar, despite a significant (up to 100 times!) difference in the laser pulse energy. We assume speed of energy releasing also affects to velocity of shock wave propagation in addition to the laser pulse energy.

5. Conclusions

The proposed numerical model has shown its efficiency and is comparable to experimental data. On average, velocity of shock wave propagation, according to the calculation results, is 30% higher than experimental data, and from 10 to 20% of laser pulse energy is transferred to shock wave energy. Different pressure distributions show generally the same behavior. It is possible to use a linear distribution of the initial conditions to simplify calculations. Analysis of the experimental data of optical breakdowns shows speed of energy releasing influences in addition to laser pulse energy. Factor of speed of energy releasing is not taken into account explicitly in Sedov theory.

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