Numerical simulation of gas propagation process behind a shock wave during optical breakdown of air in a cylindrical channel

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Abstract. This paper substantiates the need to study processes during nanosecond optical breakdown inside a cylindrical channel, and gives an analogy between L. Sedov’s theory of point explosion and an optical breakdown. A variant of the evolution of a shock wave inside a cylindrical channel is proposed. Based on the solution of the problem of a point explosion with backpressure, a preliminary estimate of the gas pressure and velocity behind the shock front was obtained to set the initial conditions in Ansys Fluent. As a result of numerical simulation, the characteristics of the shock wave were calculated, and the distributions of the velocity, density and pressure of the gas behind the shock front were obtained. According to comparison of the experiments and results of numerical simulation, an estimate of the shock wave energy is given, which is from 8 to 16\% of the energy of a nanosecond laser pulse. The results of the proposed method of numerical calculation are consistent with the experimental data for measuring the time of the shock wave exits from the channel and the target momentum at atmospheric pressure.

Keywords: Numerical simulation, optical breakdown, shock wave, cylindrical channel, theory of point explosion, gas flow in the channel.

1. Introduction

There are deepenings which formed during the high-power laser radiation of structural materials in a pulsed mode, for example, cutting or drilling \cite{1, 2, 3, 4}. It is required to know how quickly the ablation products leave the treatment area. An optical breakdown of the gas and shock waves are formed with sufficient laser power. In this work it is proposed to simulate the optical breakdown in a cylindrical channel because it is the simplest form of a depression for modeling.

One of the interesting direction is the creation of jet thrust using laser radiation. Working fluid can be heated to sufficiently high temperatures using laser energy; in practice, a specific impulse exceeding 10000 m/s is achievable \cite{5, 6}. At the moment, it is most realistic to use a laser beam of nano- and picosecond duration to create a thrust of the μN range for the satellite attitude control and stabilization system \cite{7, 8}. From this point of view the cylindrical channel can be regarded as a kind of nozzle.

An optical breakdown of the substance occurs when a certain threshold value of the laser radiation intensity is reached. The initial stage in the development of optical breakdown (gas ionization), depending on the intensity of laser radiation, is determined by a light detonation wave (LSDW) or a supersonic radiation wave (LSRW) \cite{9, 10}. After some time, on the order of a microsecond, the plasma decays and the further propagation of the shock wave is determined by the equations of gas dynamics, which can be seen in the experimental works \cite{11, 12}.
In studies on optical breakdown, it was repeatedly emphasized that the process of an optical breakdown is similar to an atomic explosion, only on a reduced scale, despite the difference in energy by a factor of $10^{14}$ [13]. Therefore, L. Sedov’s theory of point explosion can be used to set the initial conditions for numerical calculations.

The aim of the study is to obtain a method for numerical simulation of the gas propagation process behind a shock wave during optical breakdown of air in a cylindrical channel in the Ansys Fluent package and compare it with the experimental results.

2. Methods
The development of a shock wave that occurs inside a cylindrical channel (Figure 1) may look like this: an optical breakdown is initiated in a cylinder of a certain length on the back wall and propagates in a hemisphere. However, hemispheric propagation is possible only up to the intersection of the rear and side walls, then the wave will propagate along the cylinder.

![Diagram of the development of a shock wave during optical breakdown](image)

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 channel wall, the propagation of a hemispherical shock wave begins; 3 – moment of time $t_1$, the shock wave reaches the side walls and continues to propagate in the cylinder; 4 – moment of time $t_2$, the shock wave reaches the channel boundary and leaves the target.

We take the time moment when the solution ceases to be self-similar to specify the initial pressure distributions, i.e. environmental backpressure begins to show. According to [14], this is the moment when the dimensionless coordinate of the shock wave $l$ is 0.1867. For such $l$, the gas pressure behind the shock front is equal to

$$p_2 = 21.1 \cdot p_1$$

(1)

where $p_1$ – pressure of the external environment [14].

This moment was chosen because, on the one hand, the pressure difference is not so significant (with a self-similar solution, the difference is from 20 to 100 atmospheres), and on the other hand, it allows to see the initial stage of the development of a hemispherical shock wave, when it continues to grow and does not reach to the channel walls.

The coordinate of a spherical shock wave is determined

$$r_2 = l \cdot r^0$$

(2)

where $l$ – dimensionless shock wave coordinate, $r^0$ – dynamic characteristic length [14], which is defined as
\[ r^0 = \left( \frac{E_0}{\rho_i} \right)^{1/2} \]  \hspace{1cm} (3)

where \( E_0 \) – explosion energy, \( \nu \) – parameter, for the spherical case equal to 3 [14].

In [15], it is noted that the shock wave contains 30% of the energy of the supplied laser pulse. In [16], it was determined that only a small part of the energy (up to 20-25%) is converted into a shock wave when photographing a shock wave created by an optical breakdown on the surface of a plate. Moreover, when the breakdown is a hemisphere, there is a release 50% energy from the energy of a spherical breakdown, i.e. about 10-12%. It was estimated that about 9.4% of the laser pulse energy is released when compared with experimental data.

The gas velocity behind the shock front is defined as

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

where \( q = \frac{a^2}{D^2} \); \( a \) - speed of sound in an unperturbed external environment [14]; \( D \) – speed of the shock wave propagation is defined as

\[ D = 0.4 \cdot \left( \frac{E}{\rho_i} \right)^{1/2} \cdot r_2^{-3/2} \]  \hspace{1cm} (5)

where \( \rho_i \) – 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 \( E_0 \) [14], is defined as

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

Thus, the parameters at the shock front are determined. At this time, the pressure behind the wave front is 21.1 atm. and the gas velocity behind the wave front is 1010 m/s. The shock wave energy \( E_0 \) is 0.033 J, the dimensionless shock wave coordinate \( I \) is 0.1867, and the spherical shock wave coordinate \( r_2 \) is 1.281 mm. The distribution of static pressure and velocity is linear, from 0.3 \( p_2 \) at the center to \( p_2 \) at the front, from 0 m/s at the center to 1010 m/s at the front, respectively (Figure 2).

Simulation of the process in a flat setting was carried out using Ansys Fluent 17.2 software. A rectangular area was created (dimensions of about 0.02 m in length and 0.013 m in height), mesh size 0.00001 m, mesh quality 0.99. Output condition Pressure-outlet with permeable walls and pressure of 1 atm. at infinity. It is used density-based solver with inviscid model, external environment is defined as ideal gas (air). External environment pressure is 101325 Pa, temperature is 293 K.

**Figure 2.** Initial distributions of static pressure (Pa) and gas velocity behind the shock wave front (m/s)
Hemisphere area is marked to enter the value of pressure and speed and Patch operation is used to set specific values.

3. Results

Distribution of the gas velocity behind the shock wave was obtained as a result of modeling. It is possible to distinguish the initial stage (Figure 3a), the reflection of the shock wave from the channel walls (Figure 3b) and the exit of the shock wave with the removal of the main part of the gas (Figure 3c).

![Figure 3. Velocity field distribution: a) initial moment, b) reflection from the walls, c) shock wave exit from the channel](image)

Figure 4a shows the results of calculating the thrust impulse from the number of calibers. We used the distribution to calculate the thrust impulse of the axial velocity and gas density at the exit of the cylindrical channel; the results of the experiment on measuring the impulse are also given thrust cylindrical targets with a diameter of 3 and 6 mm. The tests were held at atmospheric pressure using an LQ 529B laser with a wavelength of 1064 nm, a laser pulse energy of 0.35 J, a pulse time of 10 ns and a lens focal length of 0.13 m. Figure 4b shows the results of calculating the time of shock wave movement along a cylindrical channel. We used to a schlieren method and a Memrecam HX-4 high-speed camera with a shooting rate of 400,000 frames per second to register the shock wave.
The results of numerical simulation and experiment give coinciding results for the thrust impulse and good coincidence in the time of the shock wave exit from the cylindrical channel.

4. Discussion

It is known from the theory of a point explosion that the excess pressure in the wave is distributed unevenly, but closer to the edge of the shock wave. From the center to half the length to the edge of the shock wave, there is a so-called "Pressure plateau", equal to approximately 0.3—0.4 of the pressure at the front of the shock wave. It is difficult to achieve such a distribution at such small distances; therefore, a linear distribution of the initial pressure and velocity was used (Figure 5a, 5b).
As can be seen from the Figure 5, the distribution of velocity according to Sedov tends to linear and practically coincides with the distribution in the model. The static pressure has a power law of distribution, and according to Figure 5a, with a linear pressure distribution, overestimated shock wave characteristics should be expected. This is probably why in this work an estimate was obtained that about 9.4% of the laser pulse energy is released, whereas with a pressure distribution according to Sedov this value can reach 15 - 16%.

5. Conclusions
The use of L. Sedov's theory of point explosion for setting the initial parameters of a nanosecond optical breakdown makes it possible to numerically simulate the behavior of a shock wave in a cylindrical channel. The results of numerical simulation can be used to obtain the characteristics of the shock wave, to obtain the distribution of velocity, density, and pressure along a cylindrical channel.

The results of numerical simulation are consistent with experimental work on the measurement of the thrust impulse and the time of the shock wave exit from the cylindrical channel, which makes it possible to draw a conclusion about the correct distribution of the gas velocity and density.

6. References

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