Shock wave and radiation at explosion of spherical HE charge inside a tube filled with xenon

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The operation of a powerful source of optical radiation based on explosion of spherical HE charges in metal tubes filled with xenon was investigated. The velocity and radiative characteristics of the shock wave propagating through the tube were determined. It is shown that reflective coating of pipe walls makes it possible to increase the density of the energy flux by more than an order of magnitude as well as to improve the shape of its time dependence. A three-dimensional numerical simulation of the formation and propagation of a shock wave was performed, and a simplified method for estimating the radiation intensity was proposed.

1. Introduction
To simulate the effect of continuous spectrum radiation of various nature on a substance, it becomes necessary to create and use sources with different duration, intensity and shape of the light pulse. In particular, sources of relatively low intensity of ~ 10–50 kW/cm² with duration of ~ 1 ms, which correspond to the parameters of radiation arising from powerful explosions of charges of a condensed high explosive (HE), are of interest. In the open space explosion, the shock wave (SW) decays quickly. As a result, the temperature and density of the shock-compressed gas are reduced to values at which the radiation intensity is out of practical importance. Much more effective is the technique where the explosion is carried out in a semi-confined volume of the explosion tube. When the charge size is comparable with the diameter of the tube, the SW at the initial stage is formed due to several reflections from the side wall and maintains a high intensity during propagation downstream. An additional important aspect of this technique is the technologically advantageous possibility of filling the blast tube with inert gases such as argon or xenon that significantly increases the light flux intensity. The efficiency of such radiation sources was discussed in [1], [2], [3]. The use of explosion tubes allows to vary the density of the radiation flux in a controllable manner over a wide range, as well as to achieve long exposure times. In addition, the identification of the mechanism of formation of a shock wave in a pipe during a spherical explosion can be of interest, especially for validation of the numerical simulation results.

In this work, the parameters of shock wave radiation during the explosion of the spherical HE charge in a tube filled with xenon are determined, and revealed the influence of the reflection coefficient of the walls. The analysis of the results of three-dimensional numerical simulation of the shock wave flow pattern is carried out and a method for estimating the radiation intensity is developed.

2. Experiments set up and numerical simulation
In experiments, the spherical HE charge was placed on the axis of a thick-walled metal tube near one of the open ends. The tube was filled with xenon after preliminary blowing up by argon. High-speed video recording was
carried out by SFR-2M cameras. To measure the flux density (power) and energy of light pulses, specially-made pyroelectric radiation detector with uniform spectral sensitivity in the wavelength range 0.04–1.5 μm, [4] located on the pipe axis at the tube end opposite to the charge position, were used. The SW front propagation velocity was determined using a continuous slot scan of its self-luminosity or shadow image through a slot window glued into the tube wall along its axis. According to the results of video recording, the dependence of the coordinate of the shock front on time \( R(t) \) was built. In several experiments, frame-by-frame filming was carried out from the end face of the explosion tube. In this case, an inhomogeneous luminescence pattern over the cross section due to the repeatedly reflected shock waves could be detected. In this case the position of the SW front was recorded by short-term flashes due to the reflection at the small obstacles located along the pipe. The parameters of the investigated

Table 1. Parameters of the HE charges and tubes

| HE   | PETN | TG-50 |
|------|------|-------|
| \( m, \text{g} \) | 0.8 or 2.5 | 23.5 |
| \( \rho, \text{kg/m}^3 \) | 1600 | 1700 |
| \( D, \text{m/s} \) | 7850 | 7650 |
| \( k \) | 0.3 | 0.73 |
| \( r_t, \text{mm} \) | 15 | 70 |
| \( L, \text{mm} \) | 200 | 1600 |

HE charges and explosive tubes are shown in table 1, where \( m \) and \( \rho \) - mass and density of HE charge correspondingly, \( D \) – detonation velocity, \( k \) – tube walls reflection coefficient, \( r_t \) – tube radius, \( L \) – tube length. The 15 mm tube is made from the uncoated duralumin. To increase the reflection coefficient the inner surface of the 70mm steel tube is covered by mylar film. The reflection coefficient of the pipe walls was found comparing the radiation intensity of the flash lamp placed either inside the pipe or outside it.

The radiation power from the front of the SW \( q_0 \) was found by recalculating the detector readings \( q(t) \) taking into account light multiple reflection from the pipe walls (the latter was calculated according to the procedure described in [1]). The dependence \( q_0(t) \) built in this way was compared with this one based on the xenon shock adiabat [5], [6], where the SW front velocity found by differentiating the experimental dependence of its position \( R(t) \) relative to the initiation point, was used as an argument.

To identify the details of the complex picture of the shock wave flow that occurs during the explosion of the HE charge inside a tube, a numerical simulation was performed using the GAS DYNAMICS TOOL (GDT) package [7]. Using GDT, based on the modified method of large particles, the HE explosion and subsequent propagation of a shock wave into the surrounding space investigation is implemented. The package was tested earlier on the processes of detonation and shock waves interaction with permeable obstacles [8], [9] and flat channels [10], [11]. HE explosion simulation within GDT package was also used to evaluate the explosion suppression devices efficiency [12]. The calculations were carried out in three-dimensional formulation. The computational domain included a 1/4 cross-sectional segment of a blast tube with two symmetry planes. On the left and right sides of the computational domain, a non-reflecting boundary condition was set. The size of the computational cell is 0.1 mm. When setting the task, in addition to the data presented in Table 1, the initial detonation products adiabatic index was set equal to 3, and the co-volume was also taken into account [13], [14].

Figure 1. Slot scan of the shock wave front self-luminosity.
3. Results and discussion

The HE charge explosion generates in the tube a spherical SW first. At the initial stage, this wave is undisturbed and propagates along the tube axis and attenuates according to the well-known law. Propagating in a direction perpendicular to the axis, the SW is reflected on the wall and multiply amplified. Then reflected SW returns to the pipe axis. Transverse waves “collapse” on the axis and overtake the decaying front of a spherical SW. Thus formed strong SW propagates downstream, undergoing a gradually weakening effect of transverse pressure waves. The front of this “quasi-plain” SW is a source of intense radiation. A simplified analytical approach [15] divides the process into two stages — the propagation of a spherical and subsequently plane shock wave. The technique described in [15] for air, obviously, can be applied to the HE explosion in xenon. However, it should be noted that such calculation will be approximate, since it does not take into account the complex SW formation process. The details of the flow pattern can be revealed on the base of three-dimensional numerical modeling. Figure 1 shows slot scan of the SW front self-luminosity in an experiment with a PETN charge of $m = 2.5$ g in a tube of $r_T = 15$ mm. In the slot scan mode, the dependence of the distance traveled by the shock front as a function of time $R(t)$ on the tube axis is recorded. This “one-dimensional” technique is not suitable for identifying the features of a complex three-dimensional flow pattern. Nevertheless, the experimental dependences $R(t)$ can be used, firstly, for estimating the radiation intensity and, secondly, for validating the results of numerical simulation.

Figure 2 represents a comparison of the experimental and calculated dependences $R(t)$, normalized to the radius of the explosion tube. within the case of $r_T = 70$ mm, a limited number of experimental points are given, since the moment of arrival of the shock front was determined by the method of reflection on localized barriers as described above. The results of three-dimensional numerical simulation are also presented in figure. 2. For comparison, the dependences $R(t)$ were calculated in the case of a spherical explosion in an open (not limited by the tube walls) space. As can be seen from figure. 2 there is a sharp increase of the propagation velocity of the primary (spherical) SW on the tube axis at the moment of arrival of pressure waves reflected from the wall.

The agreement between calculated and experimental results shown in figure 2 indicates that numerical modeling can be used for revealing the features of the flow pattern during the explosion of the charge in the tube, and for interpreting experimental observations as well. Figure 3 represents the
results of calculations of the pressure field at time instants corresponding to frame-by-frame filming from the end face of the explosion tube. Upon the reflection on the sidewall and the propagation of transverse pressure waves, high-temperature zones arise, which are characterized by the thickening of pressure isolines. At the initial stage, at \( t = 20 \mu s \) (figure 3), the primary spherical shock wave does not undergo transverse perturbations. In this case, the radiation intensity of its front is sufficiently large, which leads to uniform illumination over the tube cross section. At time \( t = 56 \mu s \) (figure 3), a high temperature zone appears on the pipe wall. In turn, by this moment, the radiation intensity of the front of a spherical SW is weakening. As a result, the luminescence region of the annular shape is recorded from the tube end. By the time \( t = 104 \mu s \) (figure 3), the shock front takes on a shape close to plane. Nevertheless, due to the transverse waves, there are local regions of elevated temperature on this “quasi-plane” front that is confirmed by the registration of non-uniform illumination over the tube cross section.

The energy flux density was measured using pyroelectric detectors located at a distance of 205 mm for the 15-mm tube and 1530 mm for the 70-mm tube. Figure 4a,b demonstrates a comparison of the temporal dependences of the radiation energy flux density \( q(t) \) emitted from the shock front surface. The experimentally measured dependences \( q(t) \) were recalculated to the parameter \( q_0(t) \) taking into account the location of the detector for different values of reflection coefficient \( k \) of the tube walls. The theoretical estimations were performed using the xenon shock adiabat and the results of numerical simulations. The absorption of quanta with energies \( > 10 \) eV in a cold gas was taken into account [5] under the assumption that the SW front emits as a black body, and multiple reflection of light from the tube walls [1] as well. The reflectivity measurements for 15-mm tube showed that the duralumin tube without additional inner surface treatment has a reflection coefficient \( k \approx 0.3 \), that conforms with the data obtained in special studies [16]. In experiments with 70-mm tube, the inner walls were covered by an aluminized mylar film, that allowed increasing value of \( k \) up to 0.73. In experiments when pipes with unprocessed walls were used, the calculated and experimental data are more consistent for lower values of \( k \) than the measured one. It is likely that the reflection coefficient decreases due to the evaporation of the roughness ledges of the duralumin pipes inner surface. In a mirror coating case at the beginning of...
the SW front motion, when its speed is relatively high (and, therefore, brightness), the calculation also agrees better with experiment for a value of \( k = 0.6 \) that is less than the measured value \( k \). At the later stages, better agreement is observed for \( k = 0.73 \). These features are apparently associated with changes in the reflective properties of the coating due to the interaction of its surface with radiation from the shock wave front in the vicinity of the charge (a similar effect was noted in [17]). Differences in the measured and calculated \( q_0 \) values can also be caused by gas thickness decrease in the converging and reflected shock waves arisen during the formation of a plane wave, compared with the total thickness of the compressed gas. This is illustrated by photos presented in figure 3. Zones of maximum brightness move from the pipe axis to its walls and vice versa, as this should occur when incident and reflected waves interact between each other during the formation of a plane front of a strong SW [14]. The radiation flux density from the SW front surface was also calculated using results of 3D simulation under the assumption that the gas is ideal and the SW front emits like a black body. An example of such calculation is shown in figure 4, which demonstrates good agreement with the values recalculated according to the detector readings. According to estimations, the use of mirror-reflecting walls instead of the non-reflecting surfaces gives rise to more than an order increase in the energy flux.

Generally, the calculated and experimental data demonstrate good agreement. However there are some discrepancies of the results in the near field (about several HE charge radii). It should be noted that similar problems are inherent to calculations of incident and reflected shock parameters in near field even for more simple geometry [18], [19].

4. Conclusion
It was shown that an explosion of spherical HE charges in metal tubes filled with xenon represents a powerful source of optical radiation. The velocity and radiative characteristics of the shock wave propagating through the tube were determined. It was found that reflective coating of tube walls makes it possible to increase the density of the energy flux by more than an order of magnitude. The results of three-dimensional numerical simulation of the formation and propagation of a shock wave were
compared with experimental data and a simplified technique for estimating the radiation intensity was proposed.

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