Ultra dispersed mixture of PETN and RDX for explosive welding

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Abstract. Mixed formulations of ultrafine PETN+soda and RDX+soda have low detonation velocity and small critical diameters, which makes them attractive for application to new technological processes, such as welding explosion [1]. The above properties of these formulations are due to the use of nanopowders of PETN and RDX along with a phlegmatizing agent of sodium bicarbonate. The detonation parameters of these mixtures were studied using synchrotron radiation from the VEPP-3 accelerator (Budker Institute of Nuclear Physics). Techniques we developed were applied to the measurement of density distribution in the detonation front and the width of the reaction zone, as well as volume distribution of pressure, density and spread velocities in detonation of cylindrical charges.

1. Introduction

Synchrotron radiation (SR) as a source of X-rays has a number of unique features. The main one is the possibility of recording quick movies (with a frequency of up to 8 MHz) with a very small exposure (τ < 1 ns). SR has small beam divergence, and use of a precision detector DIMEX enables recording of a multi-frame pattern of density distribution in shock waves and in a detonating high explosive, with good resolution (≈ 100 µm).

Experiments to investigate bulk detonating mixtures of ultrafine PETN and RDX with soda (35/65) of a diameter from 10 to 20 mm were carried out at an experimental station on the VEPP-3 accelerator (BINP SB RAS). The difference between these mixed high explosives (HEs) and conventional ones is due to ultrafine PETN and RDX with a grain size of < 1 µm. To this end, the explosive component is dissolved in an organic solvent (a mixture of dimethylformamide, dimethyl sulfide and acetone) and precipitated in water. After stabilization, evaporation and drying, a nanopowder with a grain size of 1.0 to 0.01 µm is obtained [2]. When mixed with sodium bicarbonate (35/65), it is an HE with very small initial density (≈ 0.5 to 1.0 g/cm³) and low detonation velocity (2 km/s and less). With a small critical diameter (≈ 2 mm), these
compositions are very promising for use in explosion welding [1]. All samples of these mixed HEs have been patented and manufactured at VNIIEF (Sarov) [2].

The experiments on VEPP-3 were carried out in two set-ups: longitudinal and lateral measurement of X-ray absorption (a detector was placed along and across the direction of detonation). SR was recorded by a DIMEX detector of in-house development [3]. The measurement procedure is given in [4, 5]. In the first experiments, we obtained the detonation velocity of mixture versus the initial density, as well as density distributions in the detonation front of these compounds. The maximum density values in the Neumann peak were 1.15 g/cm$^3$ (PETN + soda) and 1.21 g/cm$^3$ (RDX + soda) with a detonation velocity of 2.3 km/s. The width of the chemical transformation zone of these compositions is 3.0 – 4.0 mm. In the lateral absorption measurement we obtained volume distributions of pressure, density and field of velocities of spread of detonation products.

2. Experimental set-ups and results

2.1. Measurement of passed SR along detonation propagation

The experimental set-up is described in [4,5] and shown in figure 1.

![Figure 1. Experimental set-up for longitudinal measurement of absorption. D: direction of detonation in explosive charge (brown); yellow: SR.](image1)

![Figure 2. Assemblies with PETN+soda mixture prepared for experiment. 1: 15 ml syringe, 2: 20 ml syringe.](image2)

The charge preparation consisted in filling a syringe (20 ml) with the mixture and tapping the syringe until complete disappearance of cavities. The resulting density of the mixture varied from 0.50 to 0.81 g/cm$^3$ (figure 2).

In the longitudinal measurements, the mass distribution in the SR beam is recorded. In the detonation front there is observed a characteristic increase in the mass, caused by the compression of substance.

The radiation was recorded with a one-dimensional detector DIMEX-3 [3]. The detector has 512 channels with a width of 0.1 mm. The total length of the recording was determined by the width of the windows of the explosion chamber and was 18 mm. The resulting distributions of the passed radiation along the charge (frames) are shown in figure 3. Different colors show successive profiles with a step of 1.5 µs.

$z - t$ diagrams of the position of the front beginning were plotted for the mixtures under study. The resulting points were connected by an approximation line $z = Dt + c$, where $z$ is the
coordinate of the front, \( t \) is the time, \( D \) is the resulting front velocity, \( c \) is a constant. In the most cases, the error of determination of \( D \) was about 3 to 5%.

**Figure 3.** Relative intensity distribution (detector readings) vs. time. Profiles are given with interval of 1.5 \( \mu \)s. RDX + soda mixture; velocity of 2.35 km/s.

**Figure 4.** Detonation velocity vs. initial density of PETN+soda and RDX+soda mixtures.

When the initial density of the mixture is increased, the detonation velocity grows linearly (figure 4). The critical size, with which steady detonation in the mixtures was observed, was determined in experiments in plane geometry (figure 5). The cardboard box was 65 mm wide and 95 mm long. The height of the sides (the HE layer height) varied from 2 mm to 22 mm. The initiation was performed with an intermediate (booster) charge of plastic PETN.

**Figure 5.** General view of the box with PETN + soda mixture. HE layer height \( H = 3 \) mm.

**Figure 6.** Detonation velocity vs. initial height of PETN + soda mixture layer.

Figure 6 presents the detonation velocity of ultrafine PETN versus the height of the explosive layer (blue line). The red line represents data for conventional PETN, with an average grain size of 30 \( \mu \)m.

The procedure of reconstruction of density distribution in the axial part of HE sample in experiments of this type is detailed in [5]. It consists of several stages. First, the distance
dependence of the integral value \( m(X) = 2 \int_0^R \rho(X, r) dr \), the HE mass along the SR beam, which passes through the charge symmetry axis and perpendicular to it, is determined (\( R \) is the radius of the explosive charge). Since the \( m \) value varies considerably in the course of HE detonation and subsequent expansion of the explosion products, so the SR absorption spectrum changes. For this reason, each channel of the detector is subjected to pre-calibration, which enables determination of the dependence of the \( m \) value on the relative absorption of radiation by the HE under study, \( J/J_0 \), where \( J \) is the recorded SR flow and \( J_0 \) is the incident SR flow. That is done with HE samples of different thicknesses. The result of such calibration shown as the function \( \ln(J/J_0) \) of \( m \) is close to a linear function and is interpolated with a parabola \( \ln(J/J_0) = a_0 + a_1m + a_2m^2 \).

The resulting smoothed dependences averaged over several experiments \( \rho(X) \) are presented in figures 7 and 8, where \( X = 0 \) corresponds to the shock jump. Since no apparent inflections are observed on the resulting density distributions behind the Chapman-Jouget plane we mean the area where the parameters are 30% lower than those in the Neumann peak. Then, the width of the chemical reaction zone in the mixtures will be \( \sim 3 \) mm.

![Figure 7. Density profile in PETN](image)

![Figure 8. Density profile in RDX + soda detonation front](image)

An essential feature of the technique applied is the curvature of the detonation front in conjunction with its axial symmetry. When density is reconstructed from the results of recording of radiation passed through a sample, the curvature of the detonation front leads to an error. This error increases dramatically with the distance from the front, because of an assumption of spherical equidense layers in the front. For this reason, the area in which the density is reconstructed with acceptable accuracy is \( 3 \) mm at most.

### 2.2. Lateral measurement of absorption

We investigate the spread of products of detonation of a cylindrical PETN + soda charge in the set-up shown in figure 9. The experimental assembly (figure 2) was the same as in the longitudinal measurements. The lateral distribution of absorption is measured with the period between the SR pulses. The lateral distribution of mass is obtained after calibration of the absorption by the detector (figure 10). The set-up is described in detail in [4,5].

#### 2.2.1. Reconstruction of density \( \rho(r, t) \) with fixed \( z \). Iterative method.

The density reconstruction method consists in minimizing the mean square deviations of an experimental X-ray shadow (detector readings) from a density calculated from a distribution under study.
The density was sought in the form of a mesh function defined in nodes (figures 11 and 12). The density values \( \rho(z,t) \) in the intervals were complemented with interpolating splines. For better accuracy, discontinuities in the desired density distribution were found and the splines were created along weak density gradients as far as feasible.

The density values in the nodes were determined from the conditions for minimum of the function \( G(\bar{p}) \)

\[
G(\bar{p}) = \sum_{i,j} \left( F(x_j, t_i) - F^d_{p}(x_j, t_i) \right)^2,
\]
\[ F'_p(x_j, t_i) = \int \sqrt{R_0^2 - x_j^2} \rho_{\tilde{p}}(t_i, \sqrt{x_j^2 + y^2}) dy, \]

where \( \tilde{p} \) is the set of the desired density values in the nodes, \( F(x_j, t_i) \) is the experimental shadow, \( F'(x_j, t_i) \) is the shadow to test. The minimum was searched for numerically, using a simplex algorithm. The reconstruction results are presented in figures 13 and 14.

\[ \frac{\partial \rho u}{\partial r} + \frac{\partial \rho v}{\partial z} = \frac{\partial \rho}{\partial t}, \]
\[ \frac{\partial \rho u}{\partial r} + \frac{\partial \rho uv}{\partial z} + r \frac{\partial \rho}{\partial r} = \frac{\partial \rho u}{\partial t}, \]

2.2.2. Reconstruction of equation of state and mechanical parameters of flow. The method of reconstruction of fields of gas-dynamic characteristics of detonation flow is based on numerical solution to the gas-dynamical problem in a set-up corresponding to the experiment. Let us consider the problem of a cylindrically symmetric gas flow. Then in the Euler coordinates, the equations of continuity and momentum look as follows:

\( t, \mu s \)

![Figure 13. Reconstructed density distribution in PETN.](image1)

\( r, cm \)

![Figure 14. Reconstructed volume density distribution in PETN.](image2)
\[
\frac{\partial r \rho v^2}{\partial z} + \frac{\partial r \rho uv}{\partial r} + r \frac{\partial p}{\partial z} = \frac{\partial r \rho v}{\partial t},
\]

where \( \rho \) is the density, \( p \) is the pressure, \( u \) and \( v \) are the axial and radial components of the velocity vector \( v \), \( r \) and \( z \) are the radial and axial spatial coordinates, \( t \) is the time.

Let us add the boundary conditions: a flow with known parameters \( \rho_0 D \) is the mass flow; \( \rho_0 D^2 \) is the flow of the axial component of the momentum (figure 15) flows in through the flat surface of the detonation front. In the rest surface, the boundary conditions correspond to the decay of the discontinuity between the detonation products and the air.

Let us represent the unknown equation of state of the substance behind the detonation wave front in a parametric form,

\[
p(\rho) = p_0 (\rho/\rho_0)^{G(\rho)},
\]

where \( G(\rho) \) is a cubic spline based on nodes with fixed densities, \( \rho_1 \). The values of the adiabat \( G_1 \) in these nodes are the sought for unknown parameters of the equation of state.

The above system was solved numerically by the Godunov method on the Lagrange mesh.

Having full information on the density, one can compare the X-ray shadow dynamics calculated numerically and measured experimentally, and thus choose a state equation that optimally describes the experimentally measured X-ray shadow.

With the results obtained one can detail the spatial distribution of the density of the expanding products of the PETN+soda mixture detonation. Figures 16 and 18 show the resulting pressure and density distributions, as well as their values along the charge axis (figures 17 and 19) for detonation of PETN+soda (the density \( \rho = 0.75 \text{ g/cm}^3 \)). Figure 20 shows the distributions of the mass velocity vectors.

With the obtained detailed information about the flow structure, one can reconstruct the unloading adiabat \( (\rho) \) from the experimental data (figure 21). The derivative \( c = (\partial p/\partial \rho)^{1/2} \)
Figure 16. Volume distribution of pressure. $ho = 0.75$ g/cm$^3$.

Figure 17. Pressure distribution along the charge axis.

Figure 18. Volume distribution of density.

Figure 19. Density distribution along the charge axis.

will be interpreted as the speed of sound. After the reconstruction of the equation of state, it is calculated explicitly

$$c = \left(\frac{\partial p}{\partial \rho}\right)^{1/2} = [p_0(\rho/\rho_0)^\gamma(\rho/\rho + \ln(\rho/\rho_0)\gamma'(\rho))]^{1/2}.$$

Figure 22 shows charts of the speed of sound $C$, product expansion velocity $U$, and their sum along the charge axis. Equating the sum to the detonation velocity ($C + U = D$), we obtain the position of the Jouget plane (the blue dots in figure 22). The so-found Jouget plane is shown in figures 17 and 19 (the red line). In case of PETN+soda mixture and an initial density of 0.75 kg/m$^3$, the width of the chemical reaction zone is equal to 3.5 mm.

The spatial accuracy of the reconstruction of the flow characteristics is quite high; it is 1 to 2 detector channels, which is about 0.2 mm. The resulting time resolution, the statistics of the two experiments with an interval between frames of 0.125 μs taken into account, is about
Figure 20. Distribution of velocity vectors of detonation products.

Figure 21. Reconstructed equation of unloading adiabat of detonation products. $p(\rho) = p_\ast (\rho/\rho_\ast)^{G(\rho)}$.

Figure 22. Charts of expansion velocity $U_z$, speed of sound $C$ and their sum along charge axis. Blue dot: Jouget plane.

Figure 23. Chart of adiabatic index of expanding products.

0.08 $\mu$s. The accuracy of determination of the gas-dynamic parameters is adjusted using the conservation laws; it is estimated as 10% at least for a time scale of 0.5 $\mu$s.

3. Conclusions
The techniques using SR on VEPP-3 were applied to the measurement of the density distribution behind the detonation front, the reaction zone width, and dependence of detonation velocity on the initial density of ultrafine PETN + soda and RDX + soda (35/75) mixtures. The results of the measurements enabled reconstruction of volume distributions of density, pressure and flow velocities in expanding explosion products. The equation of state was derived for explosion products in the form of pressure versus density, $P(\rho)$. 


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