Tomography of gas-dynamic characteristics of the detonation flow

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Abstract. Results of studying detonation processes in plastic-bonded TATB explosive, which are obtained by methods based on using synchrotron radiation, are given. In experiments, the detonating cylindrical charge was probed in a plane perpendicular to the axis. This allows us to obtain data on the dynamics of the mass distribution on the beam in a fixed section of the examined detonation flow. For cylindrical charges, the flow of detonation products is axisymmetric. This allows us to reconstruct the density distribution along the radius in the examined charge section on the basis of information obtained by probing in one perspective only. Data on the density distribution in the detonation front and behind the front for several high explosives are presented. The data on density distribution were used for reconstruction of all parameters (density fields, particle velocity vector, and pressure) of gas-dynamic flow of products of explosion. This method is based on numerical solution of the gas-dynamic problem formulated in accordance with a condition of experiment. The form of the equation of state is set, and a field of flow is calculated, in which the density distribution with that obtained in experiments is compared. The equation state parameters were chosen by minimizing the functional of root-mean-square deviations of the calculated and experimental x-ray "shadows" of the examined flow in selected nodes of the computational domain.This method allowed to obtain parameters of barotropic equation of state of detonation products and reconstruct agreed flow with full set of gase-dynamic characteristics: density fields, particle velocity vector, and pressure.

Introduction

Aleshaev et al. [1, 2] proposed a method for studying detonation and shock-wave processes with the use of synchrotron radiation (SR) induced by operation of strong-current cyclic accelerators in the regime of pulsed generation of such radiation. The formation of a bunch of electrons on the orbit leads to generation of x-ray quantum pulses following each other with a stable time interval. A small duration of the pulse (≈ 1 nsec) ensures high accuracy of measuring the parameters of fast processes. During that time that passed after the papers were published, specialists of the Novosibirsk Scientific Center used the accelerators and other facilities of the Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences (BINP SB RAS) to perform a series of experiments in this field. Specialists from various institutes of Sarov, Snezhinsk, Moscow, and Chernogolovka participated in some experiments. The basic attention is this paper is paid to using synchrotron radiation for studying the processes of detonation of condensed high explosives (HEs), including problems of density measurements in the detonation wave and in the expanding explosion products.

General characteristics of the equipment

In all experiments described in this paper, the SR source is the storage ring of the VEPP-3 facility based at BINP SB RAS. Electrons collected into one bunch with the energy of 2 GeV pass through a deflecting magnet (wiggler) with the magnetic field induction of 2 T and form an SR pulse with the photon energy of 10–30 keV. The resultant soft x-ray radiation in this range allows effective conduction of x-ray experiments with objects having the density of 0.5–3 g/cm^2 . The x-ray component of SR offers some advantages in the dynamic experiment over the traditional sources of x-ray radiation: high intensity of the photon flux 10^6 photons/mm^2 during one exposure, low angular convergence, and high stability and periodicity of radiation flashes exposure time $\approx$ 1 nsec and repetition period from 125 nsec and higher).

The most important element of the measurement system is the DIMEX linear detector of x-ray radiation [3, 4], which was developed and fabricated at BINP SB RAS. The detector allows the x-ray radiation flux density distribution to be recorded during a time shorter than the interval between the pulses and has 256 (in the latest version, 512) channels 0.1 mm wide. The electronic circuit of the detector allows 32 frames to be recorded. The DIMEX detector was used in all experiments described here. Its spatial resolution is 0.1 mm at the 50% efficiency of detection for quanta with the energy of $\approx$ 30 keV. The detector aperture is 25.6 mm (in the latest version, 51.2 mm) in the direction of the mea sured coordinate and 2 mm in the transverse direction. The developed version is an ionization chamber with a gas electron amplifier separating the region of conversion of x-ray quanta from the gap where the charge is directed onto a scanning microband structure made with a step of 0.1 mm. The coordinate distribution of in tensity is determined from the magnitude of the charge passing through each element of the scanning structure during the exposure time. If the ionization chamber is filled by a Xe–$\mathrm{CO_2}$ mixture (80/20%) up to a pressure of 7 atm, the device ensures a resolution of 0.2 mm and detection efficiency of 50%. To reduce the overall large radiation load, a mechanical ”fast shutter” (rotating copper disk with a notch) is placed ahead of the detector to ensure the time of detector exposure in the experiment for 40 mks only.

Tomography of gas-dynamic characteristics of the detonation flow

In experiments of this cycle, the detonating charge was probed in a plane perpendicular to the axis (Fig. 1). This arrangement allowed us to obtain data on the dynamics of the mass distribution on the beam in a fixed section of the examined detonation flow. An example of such a distribution is shown in Fig. 2. Actually, to obtain a tomographic image of an object, the latter should be photographed from different perspectives. For cylindrical charges, the flow of detonation products is axisymmetric. This fact allows us to reconstruct the density distribution along the radius in the examined charge section on the basis of information obtained by probing in one perspective only. Further, with the flow being assumed to be steady, we reconstruct the complete density distribution of detonation products (i.e., we construct the function $\rho(r, z)$, where r and z are the radial and axial coordinates). It is necessary to solve illposed inverse dynamic problem of tomography, and the classical methods based on Abels inversion cannot be used here. The reason is the nonsmoothness of data obtained in experiments and the problem of their regularization. One possible solution of this problem is to develop special methods of density reconstruction, based on regularization of the sought density distribution with intense involvement of a priori information on the examined flow structure. In our case, we developed a special method of reconstructing gas-dynamic parameters of the detonation flow from the data of x-ray experiments. The method is rigorously tuned to a

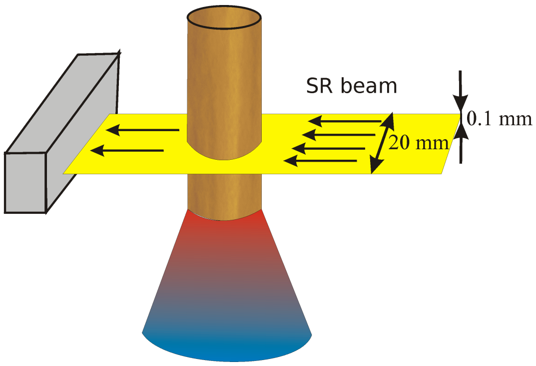


Fig. 1. Arrangement of the experiment on determining the density distribution in the detonation flow.

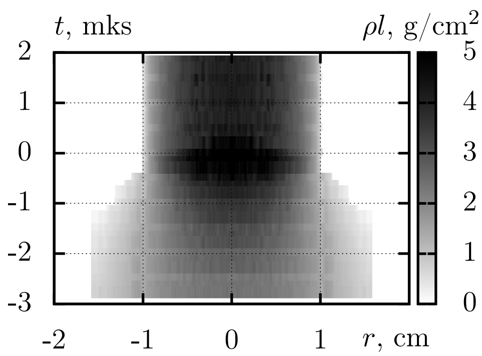


Fig. 2. Dynamics of the x-ray shadow in a fixed section during plastic-bonded TATB charge detonation.

particular problem, but it ensures not only significant improvement of the density reconstruction accuracy [5, 6], but also determination of the remaining gas-dynamic characteristics: distributions of particle velocity and pressure [7]. The developed and implemented algorithm is described below.

Algorithm of reconstruction of flow parameters and results obtained

The method of reconstructing the fields of gasdynamic characteristics of the detonation flow is based on the numerical solution of the gas-dynamic problem formulated in accordance with a particular experiment. Let us consider a problem of a cylindrically symmetric gas flow. In this case, the equations of continuity and motion in the Eulerian coordinates have the form:

$$\frac{\partial r\rho u}{\partial r} + \frac{\partial r\rho v}{\partial z} = \frac{\partial r\rho}{\partial t},$$
$$\frac{\partial r\rho u^2}{\partial r} + \frac{\partial r\rho uv}{\partial z} + r\frac{\partial p}{\partial r} = \frac{\partial r\rho u}{\partial t},$$
$$\frac{\partial r\rho v^2}{\partial z} + \frac{\partial r\rho uv}{\partial r} + r\frac{\partial p}{\partial z} = \frac{\partial r\rho v}{\partial t},$$
$$p(\rho) = p_0(\rho/\rho_{00})^{G(\rho)}.$$

where ρ is the density, p is the pressure, u and v are the axial and radial components of the velocity vector $\vec{v}$, r and z are the radial and axial coordinates in space, and t is the time. Passing to the Lagrangian coordinate system, we solve the problem of the gas flow having the equation of state $p(\rho) = p_0(\rho/\rho_{00})^{G(\rho)}$ (p_0 , ρ_{00} , and G are parameters that have yet to be determined). With specified values of parameters, we calculate the flow field in which the density distribution can be compared with that obtained in experiments.

The calculation was performed in a domain with a plane right boundary, which is consistent with the assumption on a plane detonation wave propagating over the charge with a constant velocity D. The problem formulation is illustrated in Fig. 3. The boundary condition on the input boundary was the inflow of the mass and momentum fluxes ($\rho_0 D$ and $\rho_0 D^2$, respectively); the boundary conditions on the other boundaries were determined by solving the Riemann problem on the interface between the detonation products and air. Using the Lagrangian coordinates, we were able to identify the detonation discontinuity naturally and to perform calculations only in the domain occupied by the detonation flow. Godunov's method was used for the numerical solution with varied values of the sought parameters.

The parameters to be determined were chosen by minimizing the functional of root-mean-square deviations of the calculated and experimental x-ray "shadows" of the examined flow in selected nodes of the computational domain. The dependence $G(\rho)$ was approximated by a cubic spline. The resultant problem of multidimensional minimization was solved by the simplex method described and implemented in [8].

The results obtained for a plastic-bonded TATB charge 20 mm in diameter are shown in Fig. 4, 5. Figure 6 shows the calculated unloading adiabat

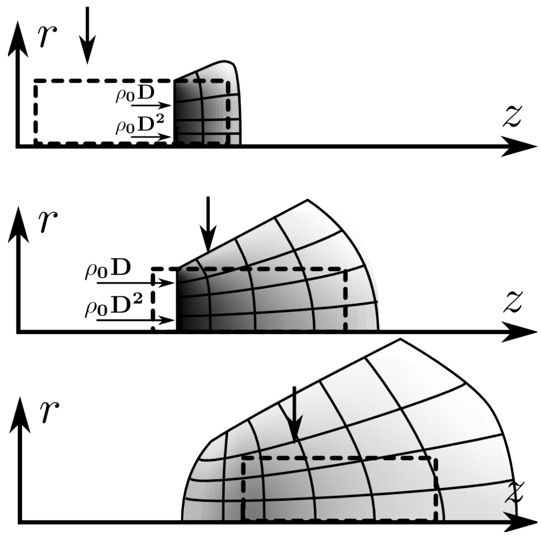
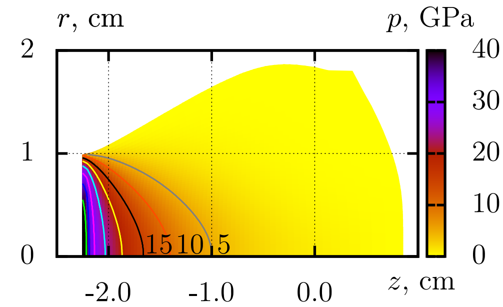


Fig. 3. Formulation of the gas-dynamic problem for calculating the detonation flow: the dashed curve shows the initial boundaries of the charge; the arrow indicates the location of the examined section.

(parameters along the streamline passing through the axis of symmetry). The calculated ratio of specific heats is close to the classical value $\gamma = 3$.

The system of equations used in the method for reconstructing flow characteristics does not involve the energy balance equation. This allows us to extend this method formally to the chemical conversion zone as well, though the assumptions made above become here somewhat incorrect. The real process in this zone is not isentropic, and the state cannot be considered as thermodynamically equilibrium. Nevertheless, the parameter distributions along the charge axis have regions of a drastic decrease in the values of the parameters, which can be approximately correlated with the chemical conversion zone. Continuing our considerations and interpreting the derivative $\partial p/\partial \rho$ as a squared velocity of sound c, we determine the position of the sonic surface from the equality $|v| = c$, which is the Chapman-Jouguet condition in the coordinate system moving with the velocity of the detonation front. The thus-calculated sonic surface is shown in Fig. 7 (points on the dependences from Fig. 5).

The spatial error of reconstructing the flow characteristics is rather low: 1–2 detector channels, which is $\approx$ 0.2 mm. Based on the statistical data



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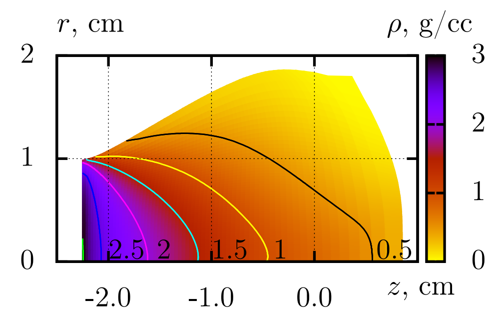

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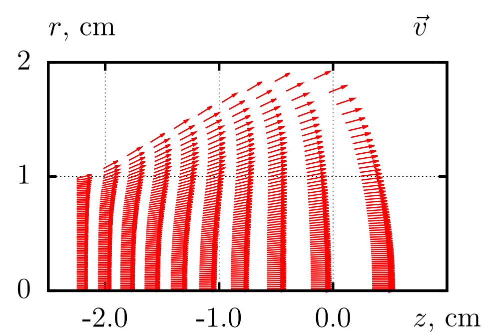

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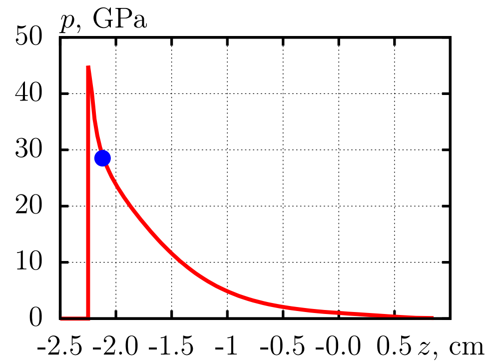
Fig. 4. Spatial distributions of parameters during detonation of a cylindrical plastic-bonded TATB explosive (density 1.85 g/cc) in 3 mks after initiation: (a) pressure; (b) density; (c) particle velocity in a fixed coordinate system; the point is the sonic boundary.



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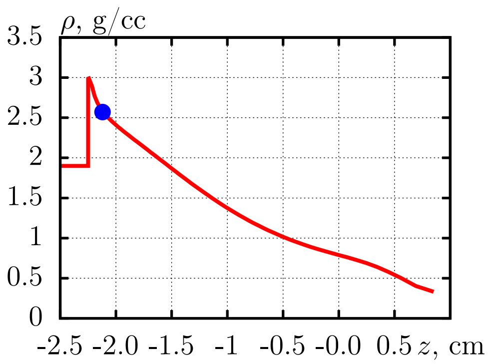

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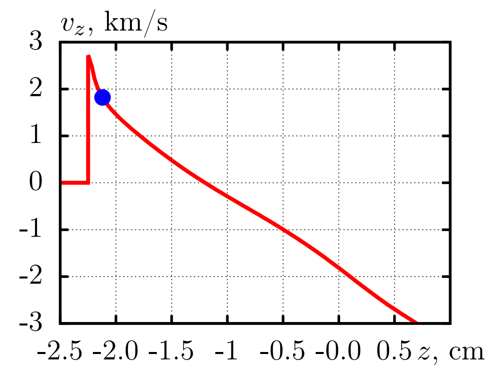

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Fig. 5. Spatial distributions of parameters on the axis during detonation of a cylindrical plastic-bonded TATB explosive (density 1.85 g/cc) in 3 mks after initiation: (a) pressure; (b) density; (c) particle velocity in a fixed coordinate system; the point is the sonic boundary.

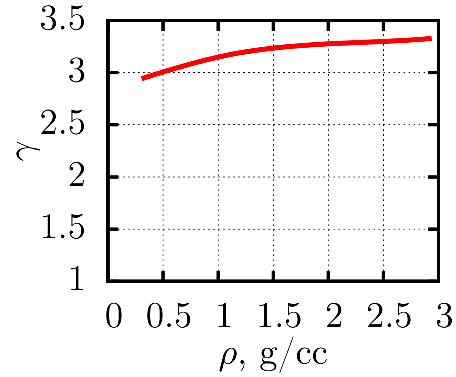

Fig. 6. Unloading adiabat of detonation products ($\partial \ln p / \partial \ln \rho$), constructed along the streamline passing through the charge axis.

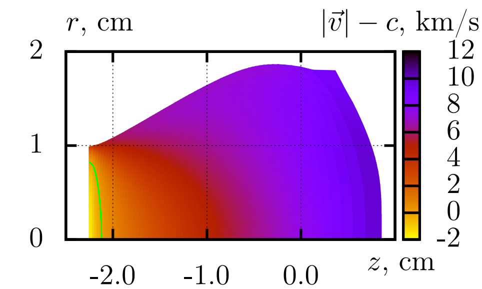

Fig. 7. Sonic boundary.

of three experiments with the interval between the frames of 0.5 mks, the overall time resolution is $\approx$ 0.2 mks. The accuracy of determining the values of the gas-dynamic characteristics is corrected by the conservation laws used and is estimated to be at least 90% at the time scale of 0.5 mks. The values obtained in the energy release zone at the time scale of 0.2 mks should be considered as estimates.

Results

Methods developed on the basis of using synchrotron radiation offer new possibilities in studying detonation processes in condensed high explosives. In the case of steady detonation, we managed to measure the density distribution on the detonation wave front and in expanding products. A method of reconstruction of the remaining gas-dynamic characteristics of the flow of detonating charges (velocity and pressure) on the basis of the space and time distributions was proposed and tested. The results allowed us to reconstruct the unloading adiabat of detonation products.

Discussion

Acknowledgments

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