X-ray transmission tomography for detonation investigation

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Abstract. This paper gives a description of a high-speed X-ray tomographic technique using synchrotron radiation and the results of its application to finding the density distribution of detonation products of condensed explosives from measurements. The data WERE obtained for a cylindrical charges of pressed pure TNT and mixture of 50% TNT with 50% RDX. The features of the employed technique and the distribution obtained are analyzed. The technique as a whole and the results obtained can be used to test and refine the known equations of state for detonation products and to construct new ones.

Introduction

Although a considerable body of information has been accumulated, steady-state detonation and the expansion of explosion products are still a subject of extensive experimental research. This is motivated by both the development of new explosives (HEs) and the need to refine available data on the characteristics of conventional HEs and eliminate ambiguity in their interpretation. Data on the expansion of detonation products are used to construct shock adiabats and to determine the coeffcients of the widely-used semiempirical equations of state and kinetics of detonation transormation. A wide range of experimental techniques based on various physical principles has been designed. Studies, as a rule, have been performed with plane onedimensional detonation waves. Al'tshuller et al. [1] proposed a conditional division of all methods for studying detonation processes into “external” and “internal.” Without a detailed characterization of all the methods used, we note that the most correct results are provided by “internal” nonperturbing methods (which do not introduce perturbations into the processes studied), among which X-ray techniques appear to provide the fullest information.

X-ray techniques have long and extensively been used to study the flow of detonation products [2–5]. Both perturbing (in X-ray measurements of the displacement of foils placed in HEs) and nonperturbing methods (in direct X-ray photography) have been implemented. One of the parameters that can be studied by such methods is the density distribution in the flow studied.

Usually, the exposure duration is fractions of a microsecond and the spatial resolution is about 1 mm. The divergence of X-ray beams produced by point sources introduces additional difficulties into the interpretation of the data obtained. Molitoris [6] employed improved sources for X-ray generation, which provided an increased temporal resolution of up to 25 nsec and a spatial resolution of up to 0.1 mm.

Advanced elementary particle accelerators produce beams of various natures with a high penetration power and unique spatial–temporal

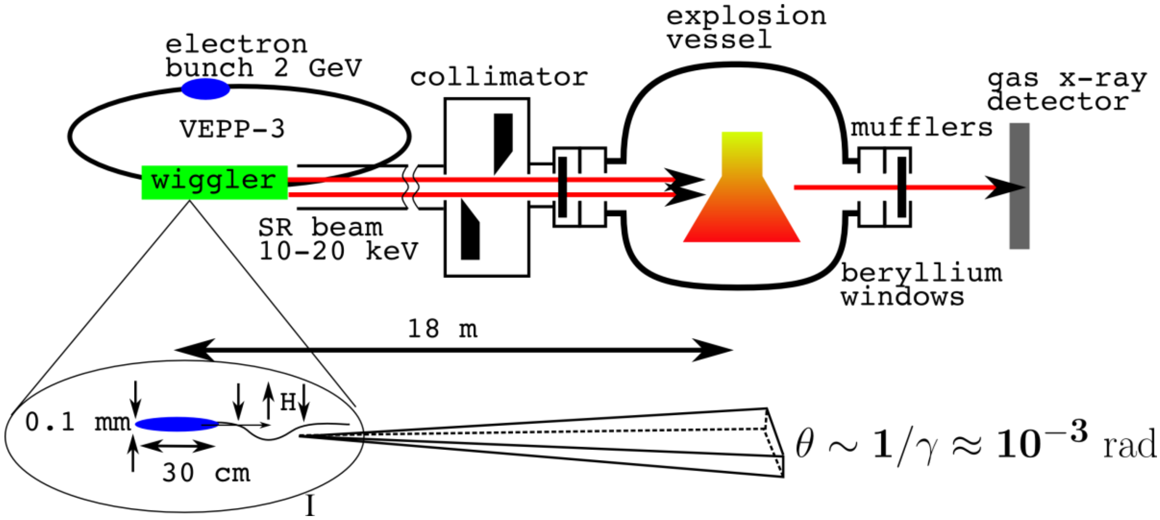

Fig. 1. Schematic diagram of explosion investigation experiments by SR.

characteristics, including nearly parallel beams. Therefore, using these facilities is a promising direction for the fundamental improvement of the spatial–temporal characteristics of the nonperturbing diagnostic techniques for studying hydrodynamic flows. In studies of shock-wave and explosive processes in condensed media, the high penetration power of beams allows, in some cases, the internal characteristics of flow to be determined using tomographic methods.

Of the possible radiation-based approaches to detonation research, two methods — proton-beam and synchrotron-radiation (SR) techniques — are now at the stage of implementation [7, 8]. The first experiments conducted with the use of proton beams are described in [9, 10]. They demonstrated the possibility of using proton radiography to study processes in condensed explosives. Much more progress has been made in the investigation of detonation and shock-wave processes using synchrotron radiation [8, 11–14]. A number of problems of steady-state detonation, the dynamics of formation of diamond particles, and deformation and failure of inert media have been solved.

The present paper describes a synchrotron radiation method and the results of using this method in tomographic studies of the density distribution of the expanding detonation products of condensed HEs. The data obtained are compared with the results of solution of a two-dimensional steady-state problem of detonation product expansion.

Experimental setup

Synchrotron radiation allows one to implement a nonperturbing internal method for measuring the spatial density distribution of detonation products of condensed HEs. The scheme of general statement presented on fig. 1. This experimental station is a part of Synchrotron Radiation and Free Electron Lasers at the Budker Institute of Nuclear Physics in Novosibirsk.

The synchrotron radiation technique for studying detonation and shock-wave processes is set out in detail in [8]; therefore, we shall only describe the experimental setup.

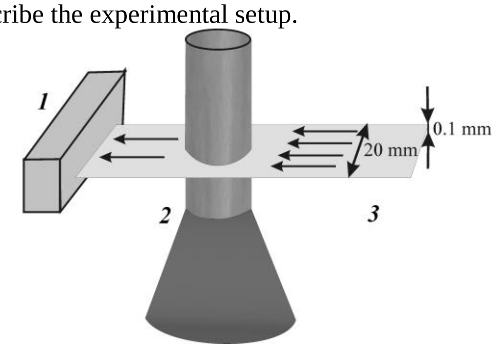

Fig. 2. Tomographic geometry: 1 – x-ray detector, 2 – investigated sample, 3 – SR beam.

The employed setup (Fig. 2) allows one to use the principles of X-ray tomography and reconstruct the density distribution in detonation products.

We studied the detonation products of cylindrical charges of pressed TNT of diameter 12.5 mm and density 1.6 g/cm^3, initiated at one end with a standard detonator. The charges had a length of 60 mm, sufficient to consider the detonation process steady-state.

The measurement region (the plane perpendicular to the charge axis) was probed with a line-focus SR beam — a beam of X-ray nonmonochromatic radiation with a flash time of 10^{-9} sec and a hardness of 10–30 keV. The quantity to be measured was the intensity of the transmitted SR beam attenuated by interaction with the material. The radial distribution of the transmitted beam intensity was measured with a DIMEX linear microstrip gas detector (see Fig. 2), which consists of 256 sensing elements spaced 0.1 mm apart and has the ability to store successive 32 frames at 0.5 μsec intervals with an exposure time of ≈1 nsec. Thus, the result of one experiment is an X-ray streak "cinema" of duration 16 μsec with a spatial width of the tested region of ≈25 mm.

Determine the amount of material on the beam from detector data

Traditionally, to obtain a tomographic image of an object, one needs to perform a survey of an object at several aspect angles. The use of charges of cylindrical shape provided axial symmetry of the detonation product flow, which allowed the radial density distribution in the observed cross section of the charge to be reconstructed using information obtained from just one aspect angle.

The results of the experiments are distributions of the radiation intensity transmitted through the tested sample at various times. Using these data, it is required to determine the radial dependence of the density of the expanding detonation products at a particular cross section. Generally, the intensity attenuation is determined by the multifactor interaction of the radiation with the material, i.e., by the dependence of the absorption coefficient on wavelength, elastic and inelastic scattering, ionization losses, bending of the beam path on the charge–air boundary and inside the tested sample at density gradients, etc. The result is additional affected by the nonlinearity of the detector and its complex spectral sensitivity.

For a further simplification of the problem, it is assumed that the degree of energy flux attenuation of the transmitted radiation – I/I_0, depends only on the integral of the density over the segment occupied by the explosion products and that the beam propagates in a straight line.

To carry out special calibrating experiments with uniform plates with different thicknesses, we can produce calibrating curve (Fig. 3). In real experiment we use this calibrating curve in reverse direction and calculate amount of material (ρd) from energy flux attenuation.

By performing measurements in various cross sections of the detonating charge, one obtains the complete spatial distribution of $\rho d(r,t)$ using the method described above. Such a surface for one of the experiments conducted is shown in Fig. 4.

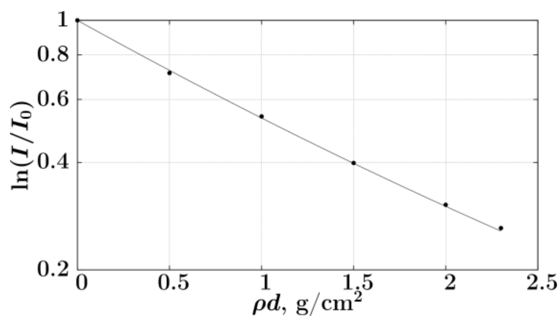

Fig. 3. Calibration curve for determining the amount of the radiographed material (TNT).

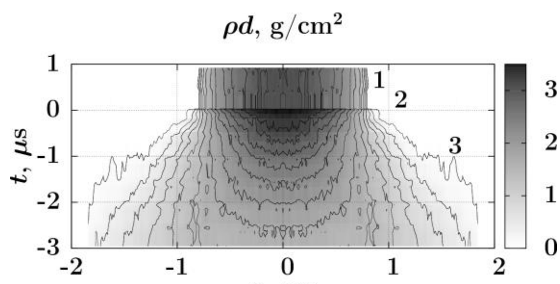

Fig. 4. Spatial distribution of the amount of the radiographed material: 1) unreacted HE; 2) detonation front; 3) detonation products. Material – TNT50%+RDX50% mixture.

Reconstructing the spatial density distribution

Obtained from experiment spatial distribution of $\rho d(r,t)$ correlate with density. X-ray shadow for every slice $F(r)=\rho d(r,t=const)$ depends on $\rho(r,t=const)$.

$$F(x)=\int_{-\sqrt{R_0^2-x^2}}^{+\sqrt{R_0^2-x^2}}\rho(\sqrt{x^2+y^2})dy\,.$$

The change of variables $r=\sqrt{x^2+y^2}$ reduces the equation to the form

$$F(x)=\int_x^{R_0}\rho(r)\frac{2r}{\sqrt{r^2-z^2}}dr\,, \qquad (1)$$

where ρ(r) is the required dependence of the density on the radius and F (x) is the experimentally measured shadow from a cylinder of radius R_0. It was shown [14] that by further transformations, the solution of the problem of reconstructing the radial density distribution is given by the formula

$$\rho(r)=-\frac{1}{\pi}\int_r^{R_0}\frac{\partial F(x)}{\partial x}\frac{1}{\sqrt{x^2+y^2}}dx\,. \qquad (2)$$

Thus, under the assumptions formulated above, the solution of the density reconstruction problem involves no difficulties if F (x) is a smooth differentiable function. In fact, the experiment provides values of F (x) in a discrete set of points, and these values are determined at a certain inaccuracy. Especially large errors in the solution of Eq. (2) using experimental data are due to inaccuracies in determining the derivative of F(x) in (2). Since the resulting distribution ρ(r, z) depends greatly on particular values of F(x) and its derivative, an accurate reconstruction of this distribution requires the development and implementation of complex algorithms for regularizing the experimental data array and solving the corresponding inverse problem. A relatively simple computational-experimental method for solving the problem in two stages was proposed to simplify the reconstruction procedure.

In the first stage, we determined the mass of the material on the beam path rather than the density. We used the above-mentioned assumption that the degree of radiation attenuation depended only on the mass of the material tested.

In the second stage, the distribution $\rho d(r,t)$ was reconstructed from the curves of ρ(r, t). According to the general concepts of the gas dynamics of detonation product expansion, the distribution of the parameters of the products should be described by smooth functions, and, hence, they can be are approximated by some appropriate functions, in which the free parameters are calculated so as to obtain the best fit to experimental data. From the aforesaid, the distribution ρ(r, z) was sought in the form of a cubic spline drawn through the nonuniformly arranged nodes of a grid which was made finer to the maximum radius of the expansion (Fig. 5). The varied parameters are the density at each node, the initial radius of the charge, and the maximum angle of expansion of the detonation products in the system of the front.

The grid density on the space and time coordinates was such that the number of nodes was suffcient for a good description of the experimental dependences ρd(r, t) and the solution obtained was suffciently smooth. Grids with a number of parameters 20–40 were used. The parameters were chosen by minimizing the standard deviations of the calculated values of ρl(r,t) from experimental values. The minimum of the function of standard deviations was sought numerically. The results of the density distribution reconstruction are shown in Fig. 6, 7.

This method has good time and space resolution to determine density in expanding wave. Unfortunate, for presented explosives we can not

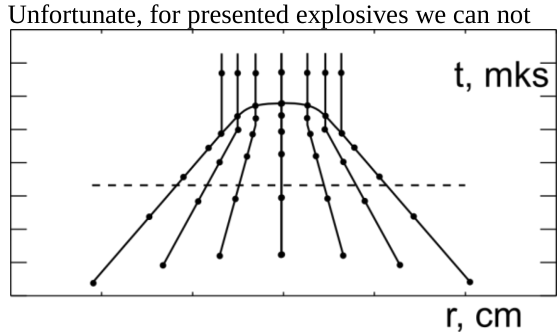

Fig. 5. Interpolation grid for density reconstruction: the squares indicate the points lying on the same beam (t = const).

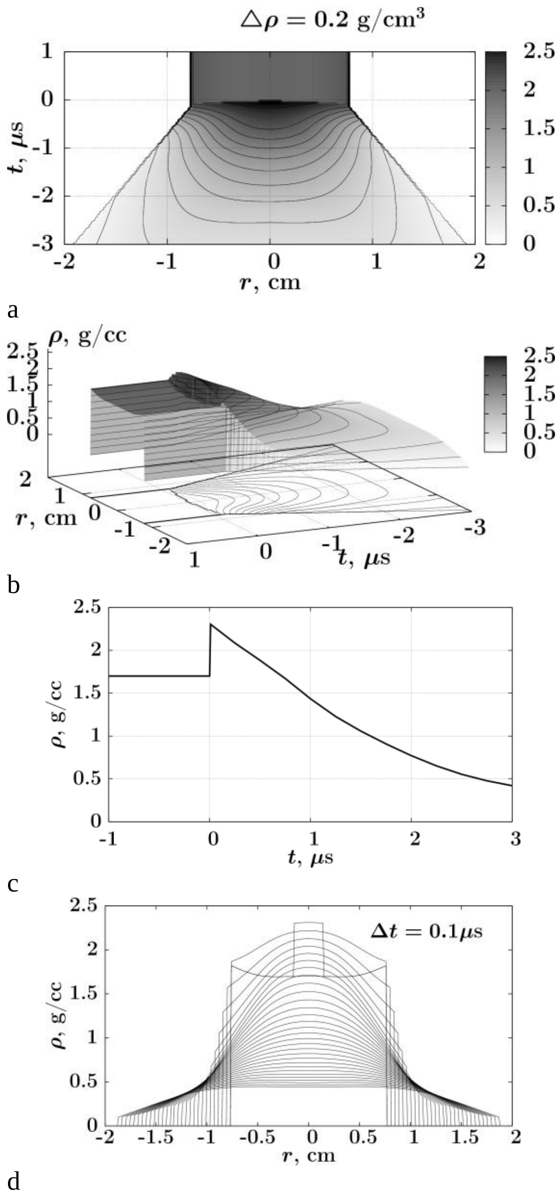

Fig. 6. Density distribution for detonation flow of 50%RDX+50%TNT mixture: a and b – surface view, c – density on axes versus time, d – density versus r for different times.

see energy release zone, and first density values relate to Chapmen-Jouge parameters.

An advantage of the given method is that the function describing the spatial density distribution can be constructed by using information from different time layers and by combining data of

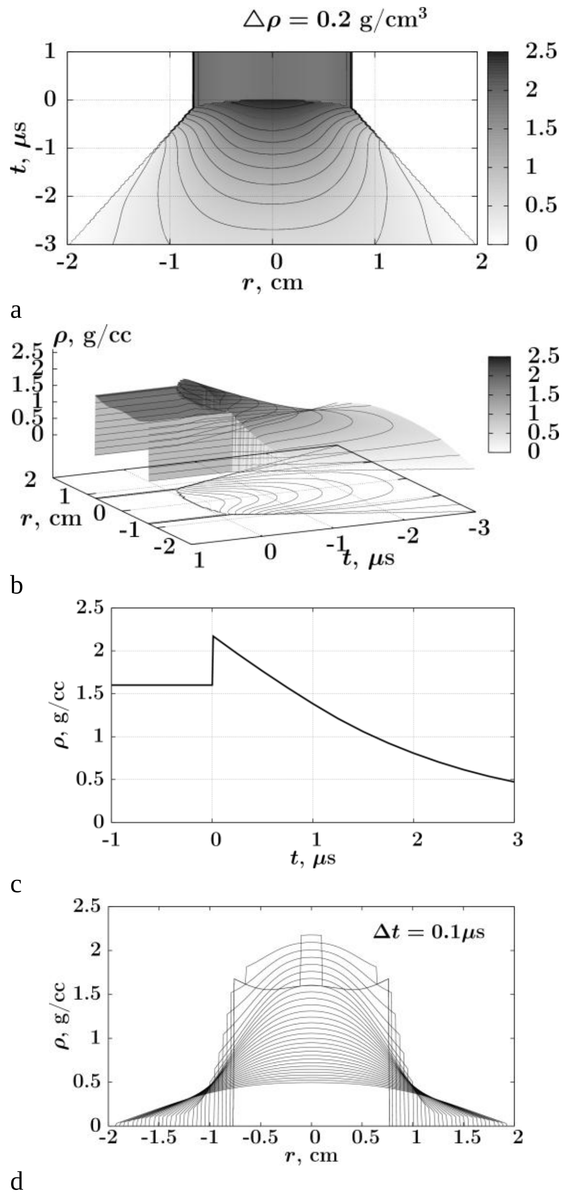

Fig. 7. Density distribution for detonation flow of pure TNT: a and b – surface view, c – density on axes versus time, d – density versus r for different times.

different experiments. In particular, the combination of the data of three experiments in one of the cases increased the reliability of the recorded parameters from a statistical point of view and improved their temporal resolution. The properties of the constructed distribution function allow it to be extrapolated to some region of coordinate values located beyond the region of experimental observation.

Some additional information can de found in [15-19].

The proposed technique provides information on the density distribution in the region of detonation transformation and product expansion; however, the current capabilities of beam generation and the existing detector parameters do not allow reliable data on the chemical reaction zone to be obtained. Measuring the density distribution in the chemical reaction zone was a subject of a separate study. The temporal resolution along the charge axis obtained using a combination of data from several experiment was estimated to be ≈0.2 μsec (1.4 mm). The spatial resolution along the radius corresponds to the step of the grid used for density reconstruction. The boundaries of the charge and the region of detonation product expansion were determined with an accuracy of ≈0.2 mm. The accuracy of density determination was ±0.2 g/cm^3 , and at low gradients and large statistics, it increased to ±0.1 g/cm^3 .

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