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High-speed X-ray transmission tomography for detonation investigation

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Abstract

This article describes the procedure and results of high-speed X-ray tomography application to reconstruct density distribution of detonation products of condensed explosives from the results of measurements with synchrotron radiation. Data obtained for a cylindrical charge (12.5 mm in diameter) of pressed TNT of density of 1.6 g/cm^3 are compared with the results of solution of the corresponding gas-dynamic problem of stationary detonation. Qualitative and satisfactory quantitative compliance of the experimental and calculated results is established. Particularities of the procedure and the distribution obtained are analyzed. It is noted that the procedure on the whole and the results can be used to define the known equations of state of detonation products more accurately and to construct new ones.

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Keywords: Explosives; Synchrotron radiation; Detonation; Density distribution

1. Introduction

The X-ray method of investigation of the flow of detonation products has for long been applied repeatedly [1–4]. One of the parameters that can be studied in this way is density distribution in the flow to study.

With the X-ray tube used, the exposure time usually amounts microsecond fractions and the spatial resolution is about 1 mm. Divergence of X-ray beams generated by point sources causes additional difficulties in interpretation of results. X-radiation in work [5] was generated using enhanced sources, which improved the time and spatial resolution to 25 ns and 0.1 mm, respectively.

The up-to-date equipment of elementary particle accelerators permits generation of rays of diverse nature, with high penetration power and unique space–time characteristics, including practically parallel rays. Therefore, such equipment is a promising way for principal improvement of space–time characteristics of non-disturbing research procedures for diagnostics of hydrodynamic flows. In the research of shock-wave and explosion processes in condensed media, in some cases, high penetration power of rays allows reconstruction of internal characteristics of flow with the help of tomographic methods.

Two procedures for investigation of detonation processes with the application of accelerator equipment are being developed now. They are based on proton beams and synchrotron radiation [6,7]. The first experiments using proton beams are described in Refs. [8,9]. They demonstrate the possibility of application of proton radiography in the investigation of processes in condensed explosives. A significant progress has been made in the investigation of detonation and shock-wave processes with the help of synchrotron radiation [7,10–12], where a number of aims in the research of stationary detonation, dynamics of diamond particle formation and deformation and destruction of inert media have been achieved.

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This work describes the way of synchrotron radiation application and presents its results in tomographic investigation of density distribution for scattering products of condensed explosive detonation. The data obtained are compared with the solution of the 2D problem of detonation products scattering.

2. Setup of the experiments

Synchrotron radiation application allows non-disturbing distance measurement of spatial density distribution of detonation products of condensed explosives. The procedure for research of detonation and shock-wave processes with synchrotron radiation application is expounded in Ref. [7]. Therefore, here, we will only dwell on the description of the setup of the experiments. The scheme used (see Fig. 1) allows applying the X-ray tomography principles and reconstruction of density distribution in detonation products.

We investigated products of detonation of a cylindrical charge (Fig. 1) of pressed TNT, with a diameter of 12.5 mm and density of $1.6\,\mathrm{g/cm^3}$. A standard detonator initiated the charge from one of the ends. The charges were 60 mm long, which was enough for considering detonation of a steady process.

The measurement area (a plane normal to the charge axis) was probed with a shaped SR beam—a non-monochromatic X-ray beam with a flash duration of 10^{-9} s and hardness of 10–30 keV. This procedure was aimed at measuring the intensity of the transmitted SR beam, attenuated due to the interaction with the substance. Radial distribution of transmitted beam intensity was measured with the linear microstrip gas detector DIMEX (2 in Fig. 1), consisting of 256 sensors spaced 0.1 mm apart and able to memorize 32 frames with a time interval of 0.5 μs and exposure time of ~1 ns. So, each of the experiments gave X-ray slit "movies" 16 μs long with a spatial width of the area under study of ~25 mm.

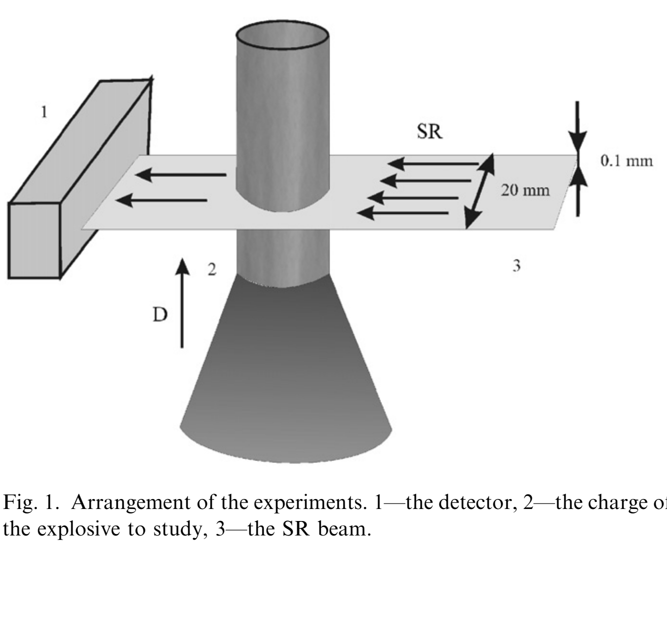

Fig. 1. Arrangement of the experiments. 1—the detector, 2—the charge of the explosive to study, 3—the SR beam.

3. Reconstruction of density distribution

Usually, to obtain a tomographic image of an object, it is necessary to shoot it from several angles. The usage of cylindrical charges provided axial symmetry of the detonation products flow, which allowed us to reconstruct density distribution along the radius in the charge cross-section under observation from information acquired at X-raying from one angle only. Assuming the flow to be stationary, we reconstruct the full distribution of detonation products density (a function $\rho(r,z)$ is created, where r and z are the radial and axial coordinates).

The experiments result in radial distributions of intensity of radiation transmitted through a sample for different moments. These data should be used to reveal the dependence of the scattered detonation products density on the radius in a particular cross-section.

In general, intensity attenuation is determined by multi-factor interaction of radiation with substance: ionization losses, elastic and non-elastic scattering, distortion of the ray path due to density gradients, etc. Moreover, the result is influenced by non-linearity and complicated spectral sensitivity of the detector.

To simplify the task some more, we will assume that the degree of transmitted radiation attenuation depends only on the density integral over the interval filled by the explosion products and that the beam itself is propagating rectilinearly. Then, introducing Cartesian coordinates x and y in the charge plane to study, we have:

$$F(x) = \int_{-\sqrt{R_0^2-x^2}}^{\sqrt{R_0^2-x^2}} \rho\left(\sqrt{x^2+y^2}\right)\mathrm{d}y$$

where $F(x)$ is the amount of mass on the beam. Carrying out the change of variables $r=\sqrt{x^2+y^2}$, we can reduce the resulting integral equation to the following canonical form:

$$F(x) = \int_{x}^{R_0} \rho(r)\frac{2r}{\sqrt{r^2-x^2}}\,\mathrm{d}r \qquad (1)$$

where $\rho(r)$ is the desired density dependence on radius; $F(x)$ is the experimentally defined shadow from a cylinder with a radius R_0. It was shown in Ref. [13] that further transformations gave the following formula for reconstruction of radial density distribution:

$$\rho(r) = -\frac{1}{\pi r}\frac{\mathrm{d}}{\mathrm{d}r}\int_{r}^{1} \frac{xF(x)}{\sqrt{x^2-r^2}}\,\mathrm{d}x. \qquad (2)$$

Thus, within the stated-above assumptions the problem of density reconstruction is not very complicated when $F(x)$ is a smooth differentiable function.

In reality, the experiment allows determination of $F(x)$ values in a discrete set of points with a certain error. Particularly, big errors in the experimentally derived solution of Eq. (2) are caused by inaccuracy of determination of the $F(x)$ derivative, appearing in Eq. (2). Since the distribution $\rho(r,z)$ so found strongly depends on specific values of $F(x)$ and its derivative, an accurate reconstruction of the distribution requires development and realization of complicated algorithms to regularize the bulk of experimental data and solution of the corresponding inverse problem. In order to simplify the reconstruction procedure, we suggest a relatively simple two-stage calculation-and-experiment method of solution.

At the first stage, we reconstructed the mass of the substance in the beam path, not the density itself. We used the above-mentioned assumption that the degree of radiation attenuation depends only on the mass of the radiographed substance, i.e.

$$\rho l = f(I)$$

where I is the detector reading; f is the unknown function, determined during calibration of the detector. Experimental data were used to define the dependence of the experimentally found intensity on the amount of the radiographed substance for each channel of the detector. We X-rayed uniform plates of different thickness (3–5 measurements). For TNT, which was used in the experiments, experimental data in the plane $\{\ln(I/I_0), \rho l\}$ are approximated well by a straight line with a small quadratic correction

$$\ln\left(\frac{I}{I_0}\right) = -0.66\rho l + 0.03\,(\rho l)^2.$$

The resulting calibration curve was used to determine the substance amount on the beam from the measured intensity of transmitted radiation. Carrying out measurements in different sections of the detonating charge and using this method, we construct a full spatial distribution of the value $\rho l = \rho l(r,z)$ (Fig. 2).

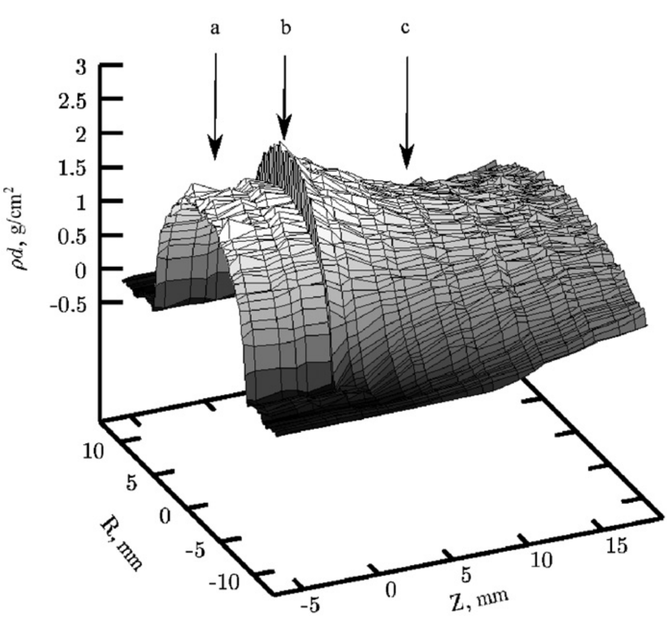

Fig. 2. Spatial distribution of the amount of the substance to radiograph. (a)—the unreacted explosive, (b)—the detonation front, (c)—the detonation products.

At the second stage, the $\rho l(r,z)$ information was used to reconstruct the distribution $\rho(r,z)$. It follows from general ideas about gas dynamics of scattering of detonation products that distribution of parameters of the products must be described with smooth functions. Therefore, the parameters can be approximated with some appropriate functions, whose free parameters are calculated on the basis of best compliance with the experimental data. So, the distribution $\rho(r,z)$ was searched in a form of cubic spline connecting irregularly situated nodes, the mesh becoming denser towards the maximal radius of scattering. The variable parameters are density values at each mesh point, the initial radius of charge and maximal angle of scattering of detonation products in the system of the front.

The mesh density in the space and time coordinates was selected so that there were enough mesh points for a good description of the experimental data on $\rho l(r,z)$ and the solution obtained was smooth enough. The reconstruction was performed using meshes with 20–40 parameters. The parameters were chosen to minimize the mean-square deviation of calculated values $\rho l(r,z)$ from the experimental ones. The minimum of the mean-square deviation function was searched numerically. Results of reconstruction of density distribution are presented in Fig. 3. Fig. 3a depicts a projection of the surface onto the space plane, which corresponds to an instant X-ray shot of a detonating charge in a conventional X-ray procedure, e.g. as in Refs. [3,4].

It can be considered as an advantage of this method that the function describing spatial distribution of density can be constructed from information from layers of different time moments, e.g. combining data of different experiments. In particular, we managed to combine data of three experiments, which has increased the validity of registered parameters, from the statistical point of view, and improved their time resolution.

The suggested procedure allows obtaining information on density distribution in the area of detonation transformation and scattering of products. However, the existing beam generation resource and detector parameters do not allow obtaining reliable data about the chemical reaction zone. Measurement of density distribution in the chemical reaction zone was an object of separate study. Estimations of the measurements show that time resolution along the charge axis, data of several experiments combined, is ~0.2 μs (1.4 mm). Spatial resolution in radius corresponds to the step of the mesh selected for density reconstruction. The accuracy of determination of the limits of the charge and the area of detonation products scattering is ~0.2 mm. The accuracy of density determination is $\pm 0.2\,\mathrm{g/cm^3}$, increasing to $\pm 0.1\,\mathrm{g/cm^3}$ in the area of small gradients and large statistics.

4. Discussion of the results

The adiabatic exponent that was calculated from the maximal value of products density, supposed to equal the density value in the Chapman–Jouget plane, is $\gamma = 2.9$–3.2.

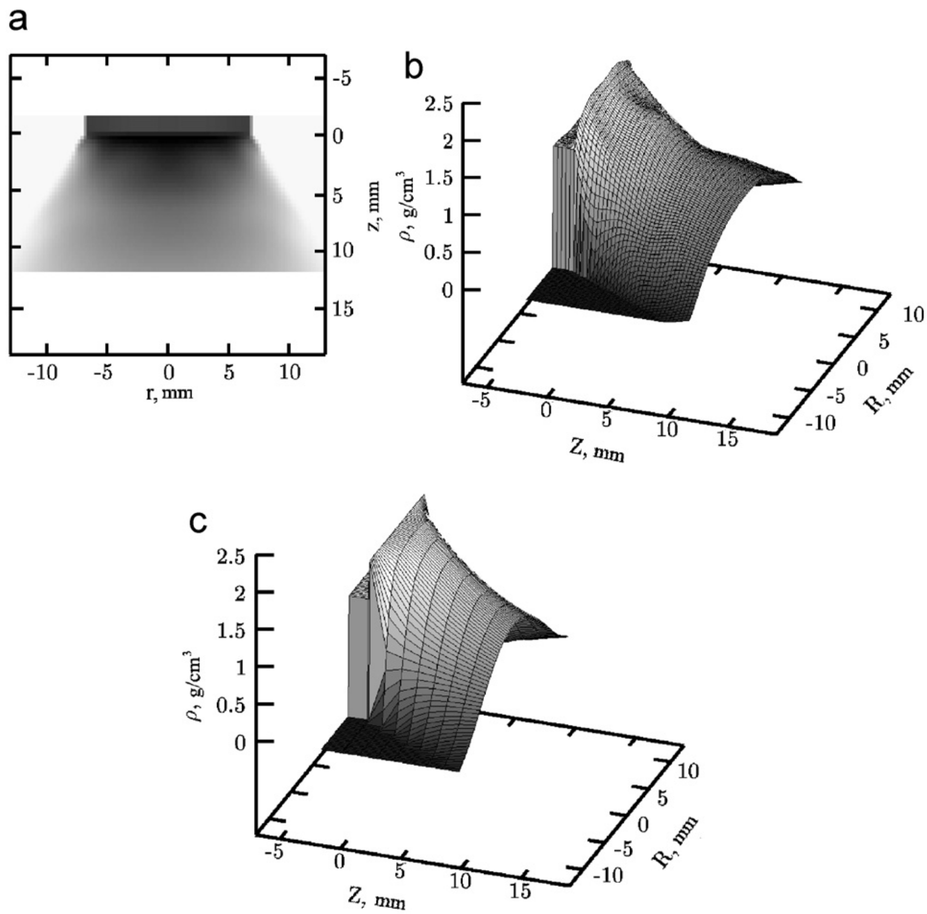

Fig. 3. Spatial distribution of the detonation products density. (a), (b)—the experiments, (c)—the calculations.

Both values comply with the data for pressed TNT, the initial density being the same, as in Refs. [14,15], for example.

Figs. 3a–c present the experimentally obtained density distribution in the form of the surface $\rho(r,z)$ and its projection onto the plane (r,z). The calculated dependences $\rho(r,z)$ are shown in Fig. 3c. In spite of the simplified statement of gas-dynamic problem (assumption of adiabaticity of detonation products with a constant adiabatic exponent), visual comparison of the experimental data with the calculations show their good qualitative compliance. A more correct quantitative comparison is shown in Fig. 4, where radial distributions of densities at different fixed distances from the detonation front are presented. The difference between the experimental and calculated values does not exceed 10%, which can be considered to be a quite satisfactory compliance, especially the approximate statement of the problem taken into account.

This tomographic reconstruction of distribution of detonation products density became possible because of the symmetry of the process. In reality there are a number of factors violating symmetry of flow. Seemingly, the main ones are non-uniformity of charges and instabilities evolving at scattering of detonation products. It has not been revealed to what extent these factors influence the accuracy of reconstruction of density dynamics. However,

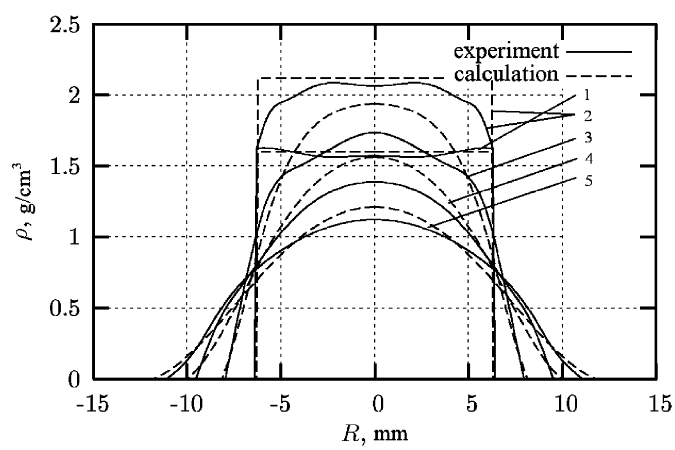

Fig. 4. Comparison of the experimental and calculated density distribution in radius at different distances l from the detonation wave front: $1-l = -2.4$ mm (the unreacted explosive), $2-l = 0$ mm (the detonation front), $3-l = 2.4$ mm, $4-l = 4.8$ mm, $5-l = 7.2$ mm.

the obtained results show a satisfactory quality of reconstruction of density dynamics.

5. Summary

This work sets forth a particular procedure for realization of possibilities of synchrotron radiation application in the investigation of explosive and shock-wave processes described in Ref. [7]. This procedure is based on a two-stage reconstruction of density distribution for scattering products of stationary detonation with construction of a calibration dependence characterizing radiation absorption by the substance and allows using the X-ray tomography principles. That is the way how the function of spatial distribution of density of TNT detonation products at an initial explosive density of 1.6 g/cm^3 was constructed. Comparison of the experimental results with the calculations showed a satisfactory compliance in the area considered, rather close to the detonation front.

The procedure in the whole and the results can be used for more accurate definition of already-known equations and for constructing new equations of state for detonation products. It should be noted that the method is also absolutely applicable to the study of behaviour of low-density inert media under shock-wave loading. Such experiments were described in Ref. [16], for example.

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