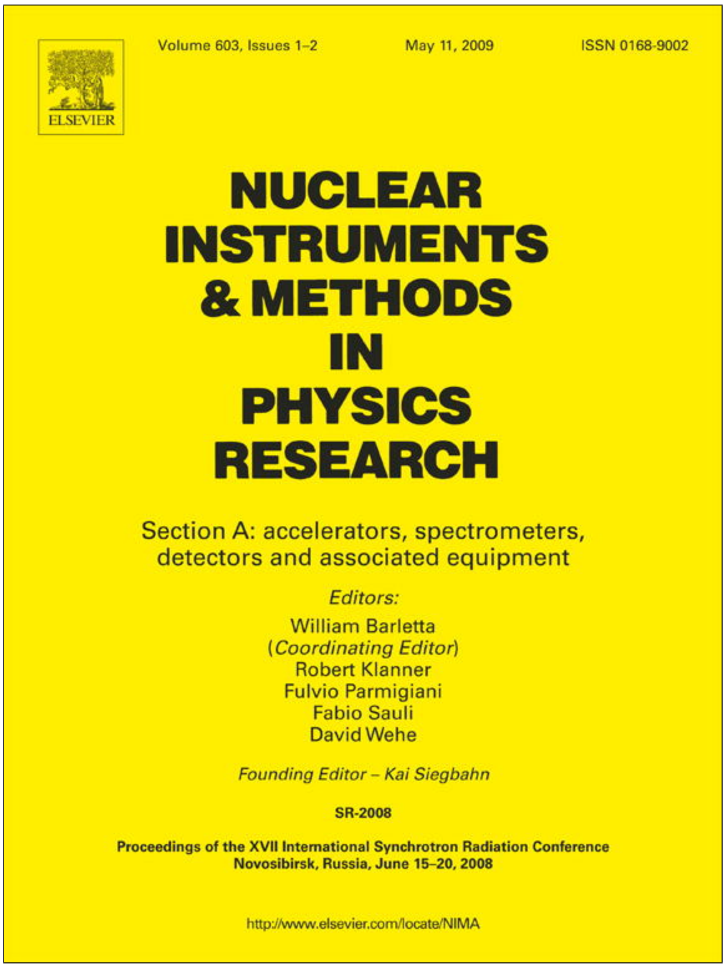

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Tomography of the flow field of detonation product using SR

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ABSTRACT

The method of extracting the parameters of gas steady-state flow (velocity field and pressure) from the spatial distribution of density known from experiment is described. The method is based on solving the equations of continuity and motion and does not require any information about the state equation. Using the data of high-speed X-ray density tomography, the spatial distributions of the velocity vector and pressure for the steady-state detonation of cylindrical charges of the pressed mixture of TNT with RDX were obtained.

1. Introduction

The procedure of high-speed X-ray tomography of density developed by us [1,2], based on raying the sample under investigation with the synchrotron radiation, allows one to record the distribution of the density $\rho(r,z)$ of detonation products of the cylindrical charges of condensed explosive. Here ρ is density, r, z are the radial and longitudinal coordinates. Using these data one may formulate the problem of extracting other flow parameters, that is, the fields of the mass velocity vector and pressure. To solve this problem, we may use a system of the equations of steady-state gas dynamics:

$$\mathrm{div}(\rho\vec{v}) = 0 \tag{1}$$

$$\mathrm{div}(\rho v\vec{v}) + \nabla p = 0. \tag{2}$$

The equation of energy conservation is not used; it is not necessary to know the equation of state of detonation products. Such a formulation is non-conventional for solving the problems of gas dynamics; generally, it is necessary to analyze the possible correct formulation of the problem. In the case under consideration, the problem becomes simpler because the flow is potential in the steady-state case. So, system (1), (2) is broken into two independent equations which are to be solved consecutively.

2. Scheme of experiment

To determine the spatial distribution of density in the products of detonation of a cylindrical charge of condensed explosive, we used the X-ray tomography procedure described in Refs. [1,2]. In experiment, an X-ray shade of the detonating charge was captured consecutively in the specific section at a 0.5 μs step between the frames (Fig. 1). The characteristics of the X-ray radiation detector used in the investigation were described in detail in Ref. [3].

The amount of rayed mass along the ray was determined on the basis of weakening of the X-ray radiation flow using the corresponding calibration.

3. Density imaging

Detonation of pressed charges made of a mixture of TNT with RDX at a ratio of 50:50% with the initial density of $1.7\,\mathrm{g/cm^3}$ was used in the work; detonation velocity was $D = 7.6\,\mathrm{km/s}$. The diameter of charges was 15 mm, the distance from the initiated end to the measurement section was 60 mm. Initiation was carried out with a plane wave generator.

Since the process is steady-state, the data are represented using a connection between time t and the spatial coordinate $Dt = z$.

The data obtained in the experiment are presented as a surface ρd in Fig. 2.

The methods of density tomography of static objects have been successfully developed by present. For dynamically changing objects, they are used with a smaller success in gas dynamics and plasma physics to determine temperature and density [4], and also in the pulse X-ray examination of density [5]. Almost in all

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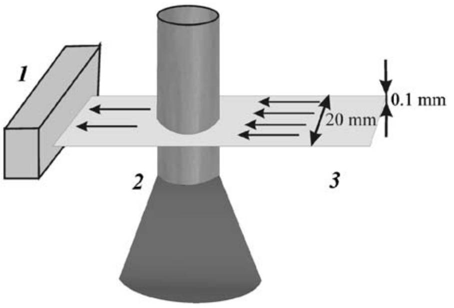

Fig. 1. A scheme of the X-ray experiment: 1—one-dimensional detector Dimex, 2—the charge of explosive under investigation, 3—synchrotron radiation ray.

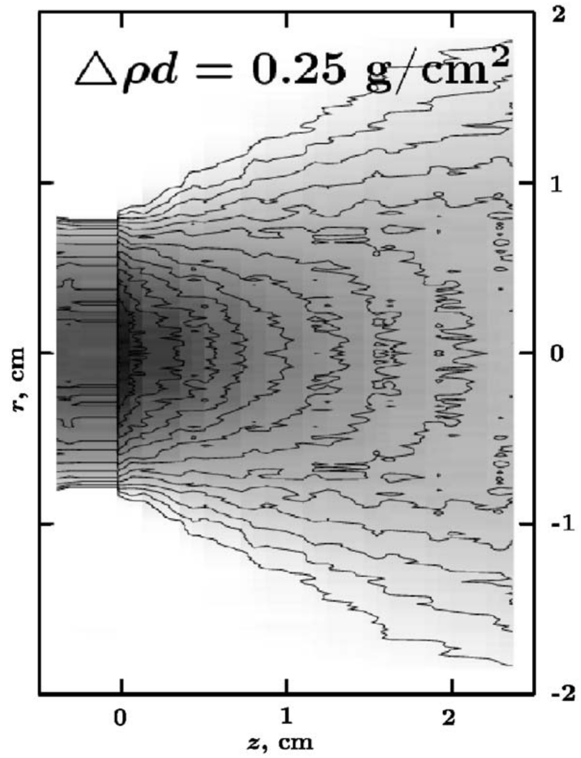

Fig. 2. Spatial distribution of the rayed matter (ρd, g/cm^2).

the cases, it is impossible to obtain the experimental data taken from several positions and with good accuracy. Because of this, the choice of an algorithm of recovery which would be stable against errors and allow efficient use of the a priori information about the object under investigation is principally important for the high-quality recovery of density.

A method of density recovery on the basis of a shade from the object under investigation proposed in Refs. [1,2] is based on regularization and uses the a priori information about the kind of the target function. This method allows one to achieve a good accuracy of the recovery of density, $\rho(r,z)$, which is necessary to recover velocity and pressure. Using this method, we have recovered the density $\rho(r,z)$ of the spreading explosion products (Fig. 3).

The distribution of density over the charge axis is shown in Fig. 4. Here $z=0$ corresponds to the position of the front of detonation wave; the density at negative z corresponds to the initial density of the charge; positive z values relate to explosion products. Insufficient accuracy of the temporal and spatial resolutions of the procedure does not allow one to carry out measurements in the energy evolution zone, and a density jump at the front corresponds to Chapman–Jouguet detonation parameters.

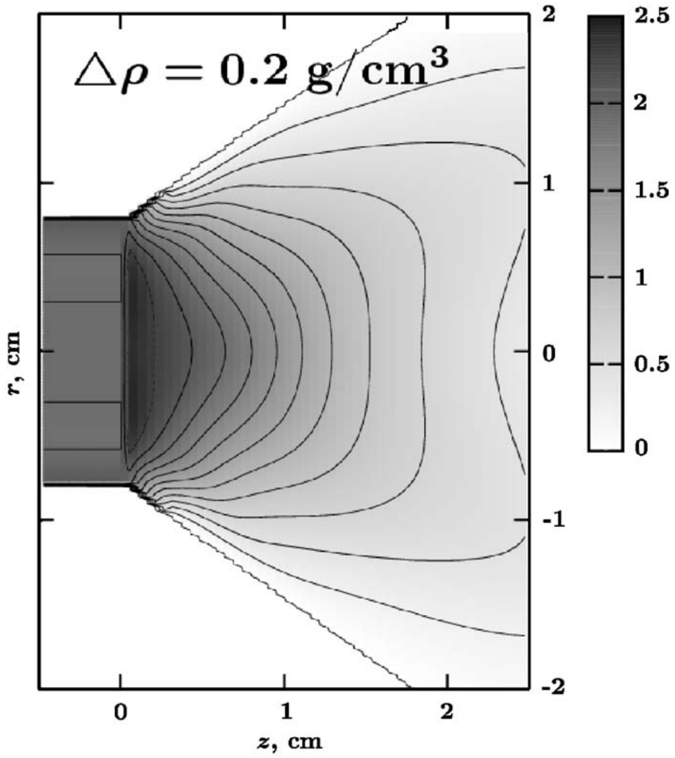

Fig. 3. Spatial distribution of density (ρ, g/cm^3).

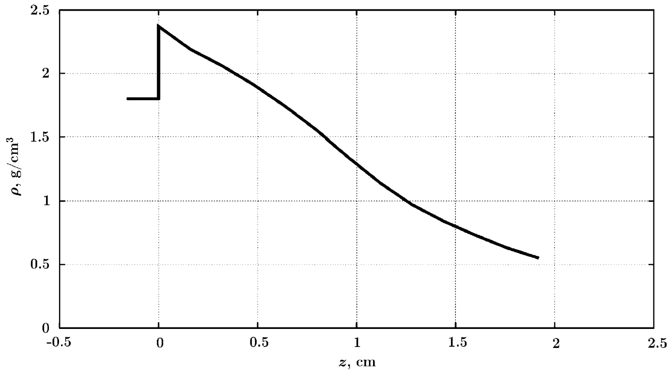

Fig. 4. Density at the axis of charge.

Estimations show that the density is measured with the accuracy of 0.1 g/cm^3.

4. Recovery of the velocity distribution

Now, using the obtained density distribution $\rho(r,z)$, it is necessary to recover the field of the mass velocity vector. Eq. (1) will be used for this purpose. Let us introduce the scalar potential of velocity $\varphi(r,z)$, $\vec{v}=\nabla\varphi$, then Eq. (1) leads to the following Laplace equation:

$$\operatorname{div}(\rho\nabla\varphi)=0. \tag{3}$$

Then, it is necessary to solve Eq. (3) in the axisymmetric region occupied by the flow under investigation, with the corresponding boundary conditions.

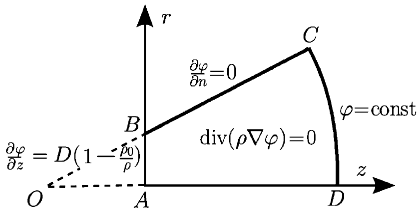

Fig. 5. Calculated region for the velocity potential.

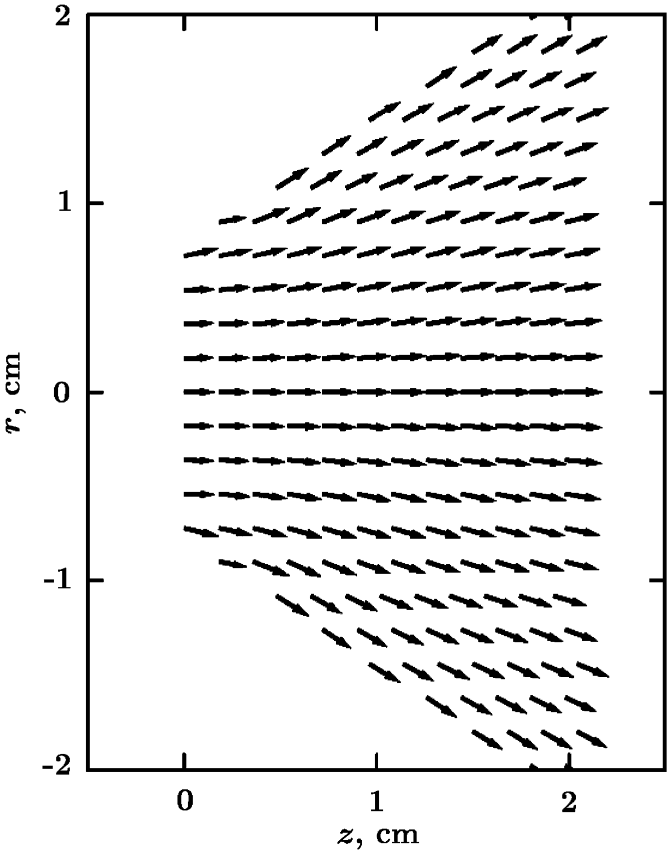

Fig. 6. Velocity field in the system associated with the front of the detonation wave.

The calculated region may be represented as a truncated cone with the base *CD* shaped as a part of a sphere (Fig. 5). The side *AB* corresponds to the surface of the detonation wave front. It is assumed that it is flat and the mass velocity on it has only an axial component determined form the mass conservation law $\rho_0(r)D = \rho(r)(D - u_z(r))$.

Here $\rho_0(r)$ and $\rho(r)$ are the dependencies of density on radius in the initial charge before the arrival of the detonation wave and immediately after, respectively, D is the velocity of the detonation wave, $u_z(r)$ is the mass velocity behind the front.

The *BC* side corresponds to the contact boundary of detonation products with the atmosphere. It is assumed to be a straight line at which the density drops down to zero, while the velocity has only the tangential component.

The *CD* side is rather remote, the inertial spread of explosion products occurs on it with a constant velocity. One cannot precisely determine the boundary condition at this line using only the mass balance equation, so we will approximately consider the substance to move here along the rays coming out of the vertex of the cone formed by the boundary of the region of detonation product spread (point *O*). The mass velocity on this surface has only the normal component, while the potential is constant.

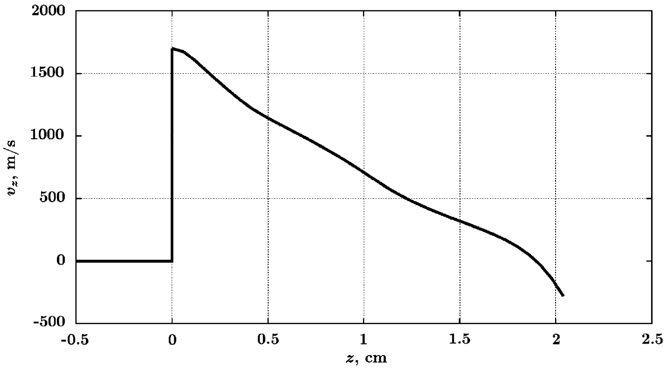

Fig. 7. Mass velocity along the charge axis in the laboratory system.

The axial symmetry of the problem turns the radial component of the mass velocity to zero on *DA*.

The listed boundary conditions are sufficient for the unambiguous solution to Eq. (3). This equation was solved numerically by means of iterations. As a result, the full field of the vector of mass velocity of the flow was obtained (Figs. 6 and 7).

The accuracy of velocity determination near the front approximately corresponds to the accuracy of density determination and is equal to 10%. At the opposite boundary of the calculation region ($z \approx 2$ cm), the effect of the chosen boundary conditions ($\varphi =$ const) is essential, and the error may reach 100%.

5. Calculation of pressure distribution

To recover the spatial distribution of pressure, Eq. (2) can be split into two parts:

$$\frac{\partial\rho v_z^2}{\partial z} + \frac{1}{r}\frac{\partial r\rho v_z v_r}{\partial r} = -\frac{\partial p}{\partial z} \tag{4}$$

$$\frac{\partial\rho v_r^2 r}{\partial r} + r\frac{\partial\rho v_z v_r}{\partial z} = -r\frac{\partial p}{\partial r}. \tag{5}$$

Differentiating Eq. (4) by z, Eq. (5) by r and summing up taking the corresponding coefficients we obtain Poisson's equation for pressure as

$$\Delta p = -\left(\frac{\partial^2\rho v_z^2}{\partial z^2} + \frac{1}{r}\frac{\partial^2\rho v_r^2 r}{\partial r^2} + \frac{2}{r}\frac{\partial^2\rho v_r v_z r}{\partial rz}\right) \tag{6}$$

where the right-hand part is the already known function. Eq. (6) is solved in the same calculation region as Eq. (3).

The boundary conditions at the *AB* side are determined from the conservation of mass flux and impulse at the discontinuity. At the sides *BC* and *CD*, pressure drops down to small values in comparison with the maximal ones; it was accepted to be zero in calculations.

At the *DA* axis, the symmetry conditions was used; then $\partial p/\partial r = 0$. Eq. (6) was solved numerically by means of iterations, similar to Eq. (3). The results of pressure distribution recovery $p(r,z)$ are shown in Figs. 8 and 9.

The accuracy of pressure recovery corresponds to the accuracy of velocity determination; it is 10% in the vicinity of the front and increases at a large distance from the front to 100%.

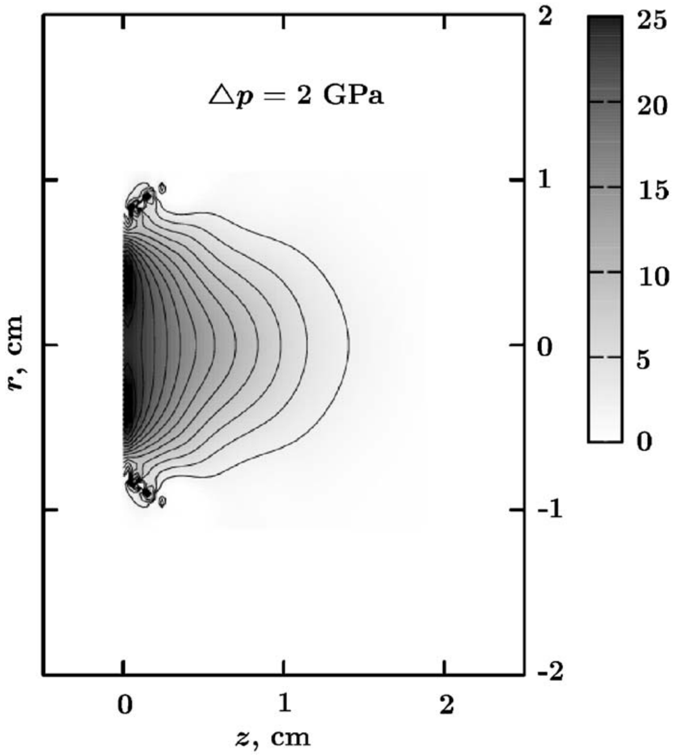

Fig. 8. Spatial distribution of pressure.

6. Conclusion

A method for determining the gas dynamic parameters of the steady-state gas flow (the fields of mass velocity vector and pressure) on the basis of the known spatial distribution of density is proposed.

An important feature of the method is the absence of the necessity to know the equation of state of the medium to solve the corresponding gas dynamic problem. To obtain the density distribution, the data of the previously developed high-speed X-ray density tomography were used.

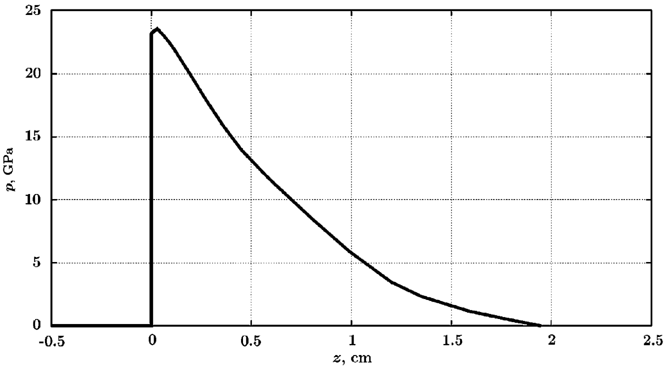

Fig. 9. Pressure distribution along the axis.

For the first time, the spatial distributions of velocity and pressure in the products of steady-state detonation of cylindrically symmetric charges of the pressed mixture of TNT with RDX were obtained with the help of the proposed procedure.

Acknowledgments

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