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CALCULATION OF THE EXPLOSION OF A GASEOUS SPHERICAL CHARGE IN AIR

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INTRODUCTION

The problem of the explosion of a spherical charge in air has been solved by numerical methods in one approximation or another [1-4]. The original calculations were made within the framework of the theory of a point explosion [1, 2]. A further refinement of the problem was discussed in [3], where, in calculations of the explosion of a spherical charge of Trotyl, account was taken of the dimensions of the charge and the behavior of the detonation products. With such a statement of the problem, the basic characteristics of the flow behind the front of a blast wave were obtained, reflecting the experimental results more exactly. An investigation of the effect of the initial pressure of the air and the specific energy of the charge on the parameters of the flow behind the front of a blast wave was made in [4]. In [5, 6] it was shown experimentally that, with the explosion of a spherical charge of explosive consisting of a detonating gaseous mixture, a shock wave is propagated in the air, analogous to the wave arising by the explosion of condensed explosives. On the basis of the results of [5] there appears, in principle, the possibility of a numerical solution of the problem of the explosion of a gas mixture. Since the radius of a gaseous charge is an order of magnitude greater than the radius of a charge of condensed explosive, equivalent with respect to the amount of energy evolved, then in the statement of the problem its dimensions cannot be neglected. In the present work, the Neumann—Richtmyer pseudoviscosity method [7] is used to solve the problem of the propagation of shock waves in air, arising with the explosion of a spherical charge of an explosive gaseous mixture. Quantitative information is obtained on the flow of air and detonation products behind the front of a blast wave for gaseous mixtures of acetylene and propane with air. In these mixtures, the combustible was taken in a stoichiometric ratio with oxygen: 1) $C_2H_2 + 2.5O_2 + 9.4N_2$; 2) $C_3H_8 + 5O_2 + 18.8N_2$. The results of the calculations are compared with the experiments of [5].

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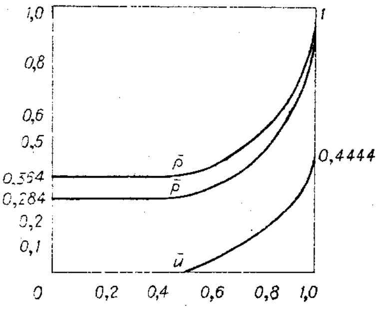

Fig. 1

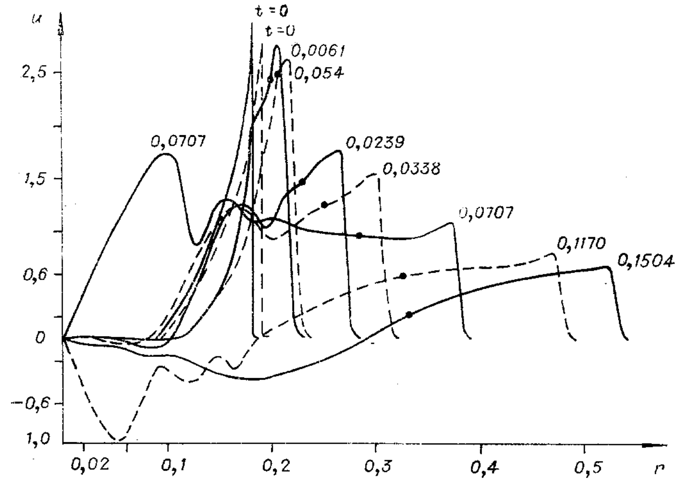

Fig. 2

1. Statement of Problem

In Lagrange variables, the explosion of a spherical charge is described by a system of equations of one-dimensional gasdynamics, which, in dimensionless form, can be written in the following manner:

$$\frac{\partial u}{\partial t} = -\left(\frac{r}{\lambda}\right)^2 \frac{\partial p}{\partial \lambda}; \quad \frac{\partial r}{\partial t} = u; \quad v = \left(\frac{r}{\lambda}\right)^2 \frac{\partial r}{\partial \lambda}; \quad \frac{\partial e}{\partial t} = -p\frac{\partial v}{\partial t}, \tag{1}$$

where $p = P/p_0$ is the pressure; $u = U/\sqrt{p_0/\rho_0}$ is the velocity; $v = V\rho_0$ is the specific volume; $e = E\rho_0/p_0$ is the internal energy; $t = T\sqrt{p_0/\rho_0}/w$ is the time; $r = R/w$ is an Euler coordinate; $\lambda = \Lambda/w$ is a Lagrange coordinate, all in dimensionless units; $w = (W/p_0)^{1/3}$W is the total energy of the charge; p_0, ρ_0 are the initial pressure and density of the air, equal, under normal conditions, to the following values: $p_0 = 1.01375 \cdot 10^5$ N/m^2, $\rho_0 = 1.293$ kg/m^3.

We assume the air and the detonation products to be ideal gases, with the equations of state $p = (\gamma - 1)e/v$ for air, $p = (k-1)e/v$ for the detonation products, where $\gamma = 1.4$, $k = 1.25$. The boundary conditions at the center of the explosion: $\lambda = 0$, $u = 0$; ahead of the front of the shock wave: $u = 0$, $p = 1$, $v = 1$.

To solve the problem, we need to know the values of the sought functions p, u, v, e, at the moment when the detonation wave reaches the boundary of the charge.

The initial distribution of the parameters in the detonation products at the moment when the blast wave reaches the boundary of the gaseous charge is found by numerical solution of the self-similar problem for a spherical blast wave [8], which is described by the following system of equations:

$$\frac{d \ln z}{dx} = \frac{(1-x)\frac{d \ln y}{dx} - (k-1)}{(3k-1)x - 2} = \frac{(1-x)^2 - y}{x\left[3y - (1-x)^2\right]},$$

where $z = R/T$; $x = U/z$; $y = c^2/z^2$; R is a spatial variable; T is the time; U is the mass velocity; c is the speed of sound in the detonation products.

The conditions at the front of the blast wave have the form

$$p_n = \rho_1 D^2/(k+1), \quad u_n = D/(k+1), \quad \rho_n = \frac{k+1}{k}\rho_1,$$

where D is the rate of detonation; ρ_1 is the density of the mixture. The distributions of the pressure $\bar{p} = P/p_n$, the density $\bar{\rho} = \rho/\rho_n$, and the mass velocity $\bar{u} = U/D$, calculated with $k = 1.25$, are shown in Fig. 1.

At the moment when the blast wave reaches the boundary of the gaseous charge, there is decomposition of an arbitrary discontinuity. A shock wave passes into the air, and a rarefaction wave over the detonation products. To determine the initial parameters of the shock wave, p_s and u_s, the following relationships are used [8]:

$$\frac{u_s}{D} = \frac{3k-1}{k^2-1} - \frac{2k}{k^2-1}\left(\frac{p_s}{p_n}\right)^{\frac{k-1}{2k}} = \frac{1}{D}\sqrt{\frac{2(p_s - p_0)^2}{\rho_0\left[(\gamma+1)p_s + (\gamma-1)p_0\right]}}.$$

The distribution of the parameters p(r, 0), u(r, 0), v(r, 0) e(r, 0) obtained were taken as the initial distributions in solution of the finite-difference problem.

TABLE 1

Composition of mixture	ρ_1, kg/m^3	Q, J/kg	k	D, m/sec	η	μ
$C_2H_2+2{,}5O_2+9{,}4N_2$	1,21	4180·815	1,25	1870	0,1804	0,28445
$C_3H_8+5O_2+18{,}8N_2$	1,25	4180·668	1,25	1730	0,1970	0,3039

2. Method of Calculation

The calculations were made using the Neumann–Richtmyer method of pseudoviscosity [7], which makes it possible to make the calculation without the isolation of singularities. The finite-difference equations approximating the system (1.1) are written in the form

$$\frac{u_i^{n+1}-u_i^n}{\tau} = -\left(\frac{r_i^n}{\lambda_i}\right)^2 \frac{p_{i+1/2}^n + q_{i+1/2}^n - p_{i-1/2}^n - q_{i-1/2}^n}{\lambda_i - \lambda_{i-1}};$$

$$\frac{r_i^{n+1}-r_i^n}{\tau} = u_i^{n+1}; \quad v_{i+1/2}^{n+1} = \frac{\left(r_{i+1}^{n+1}\right)^3 - \left(r_i^{n+1}\right)^3}{\lambda_{i+1}^3 - \lambda_i^3};$$

$$q_{i+1/2}^{n+1} = \begin{cases} 4.5\left(\dfrac{\lambda_{i+1}-\lambda_i}{\tau}\right)^2 \dfrac{\left(v_{i+1/2}^{n+1} - v_{i+1/2}^n\right)^2}{v_{i+1/2}^{n+1} + v_{i+1/2}^n}\left(\dfrac{\lambda_{i+1}}{r_{i+1}^{n+1}}\right)^4, & \text{if } v_{i+1/2}^{n+1} - v_{i+1/2}^n < 0, \\ 0 & \text{if } v_{i+1/2}^{n+1} - v_{i+1/2}^n \geqslant 0; \end{cases}$$

$$e_{i+1/2}^{n+1} = e_{i+1/2}^n - \left(\frac{p_{i+1/2}^{n+1} + p_{i+1/2}^n}{2} + q_{i+1/2}^{n+1}\right)\left(v_{i+1/2}^{n+1} - v_{i+1/2}^n\right);$$

$$p_{i+1/2}^{n+1} = (L-1)\, e_{i+1/2}^{n+1} / v_{i+1/2}^{n+1}, \text{ where } L = \begin{cases} k, & \text{if } i \leqslant i_0 - 1, \\ \gamma, & \text{if } i > i_0 - 1. \end{cases}$$

Here q is the pseudoviscous pressure, and the subscript i_0 corresponds to the interface between the detonation products and the air. The calculating scheme is explicit; therefore, the value of the time spacing was so selected that the Courant condition would be satisfied:

$$\tau < \min_i \left(M \frac{r_{i+1}^n - r_i^n}{\sqrt{\gamma p_{i+1/2}^n v_{i+1/2}^n}} \right).$$

In the calculations, M was assumed equal to 0.4.

3. Results of Calculations

The starting characteristics of the explosive gas mixtures, used in the calculations of [5], are given in Table 1, where Q is the specific energy of the charge per unit of mass; η and μ are dimensionless similarity parameters, which have the form

$$\eta = \left(\frac{3p_0}{4\pi\rho_1 Q}\right)^{1/3}, \quad \mu = \left(\frac{p_0}{\rho_0 Q}\right)^{1/3}.$$

For gas mixtures, by virtue of the fact that $\rho_1 \sim 10^{-3}\rho_{con}$, the parameter η is an order of magnitude greater than for condensed explosives.

Figures 2 and 3 show the distributions of the velocity as a function of the radius at fixed moments of time for fuel–air mixtures of acetylene with air (solid lines) and propane with air (dashed lines). The time is reckoned from the moment when the blast wave reaches the boundary of the spherical gas charge. Profiles of the velocity and the blast wave ($t=0$) and, for other moments of time, of the distribution of the shock wave in the gas are shown in Fig. 2. At the center of the charge, a compression wave passes over the detonation products, which is gradually converted into a second shock wave. Approximately at the moment of time $t=0.13$, the second shock wave is reflected from the center. After a certain time, it passes through the contact boundary and moves behind the main shock wave (see Fig. 3). From the interaction between the contact boundary and the second shock wave, a third shock wave is formed, which moves toward the center of the explosion, is reflected from it, etc. The pressure as a function of the radius at fixed moments of time is illustrated in Figs. 4 and 5. For the purposes of a comparison between the calculations and experimental results in Figs. 4 and 5, there is plotted the band of the maximal pressures at the front

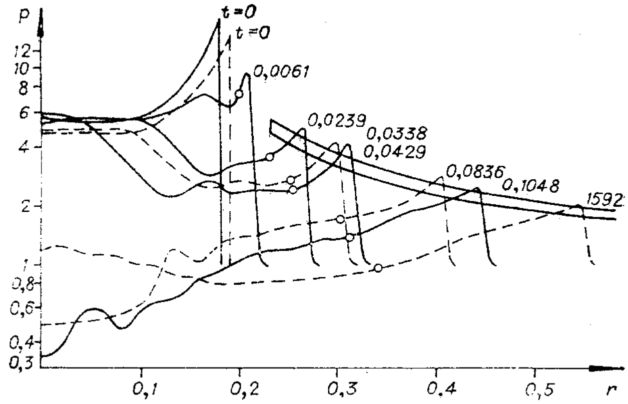

Fig. 3

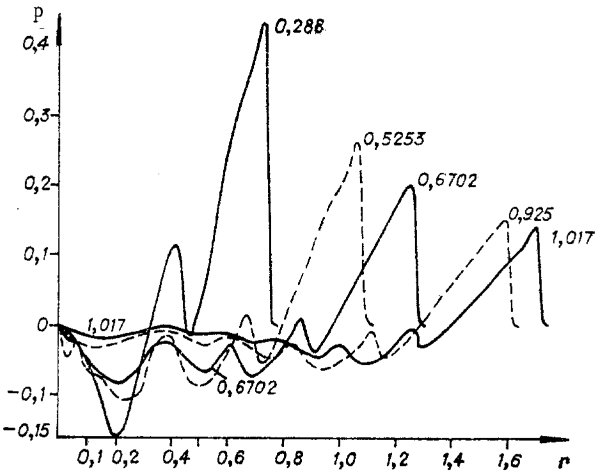

Fig. 4

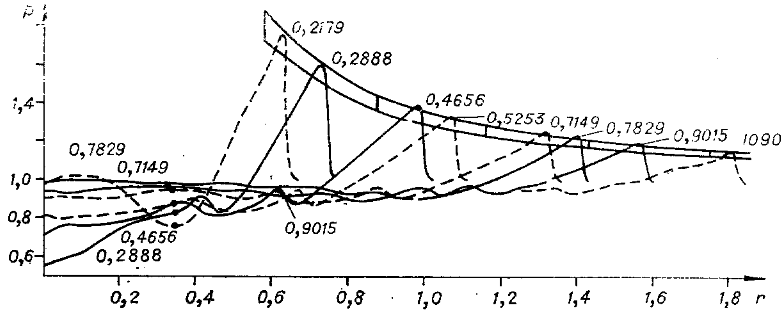

Fig. 5

of the main shock wave, taken from [5]. The width of the band corresponds to 10% accuracy of the experimental results. It can be seen from the figures that, with calculations, the values of the maximal pressures are somewhat greater than in experiments. The divergence of the results is obviously connected with the mathematical idealization of the real physical phenomenon.

The small circles on the curves denote the positions of the interface between the detonation products and the air. At the initial moments of time after the explosion, the detonation products expand and, at the moment of time $t=0.3$, occupy a maximal volume, whose radius is $1.94R_0$, where R_0 is the initial radius for the mixture. After this, there are vibrations of the contact boundary, and the final radius of the volume occupied by the detonation products is equal to $1.8R_0$. The calculations were made up to a distance of 10 R_0 from the center of the explosion. The reliability of the calculations was verified not only using the experimental results of [5], but also by reducing the spacing of the finite-difference grid. For this purpose, the spacing with respect to the spatial variable of the finite-difference problem was decreased by two times. The results obtained in the reduced grid coincided sufficiently well with the starting results on the original grid.

Thus, a numerical solution has been used to determine the distribution of those sought quantities which cannot be obtained experimentally; an effect of the pulsations of the detonation products of a gas charge has been obtained; an analogous distribution for the detonation products of condensed explosives was not observed in experimental work [5]; a calculating scheme has been approved which makes it possible to solve the problem for a whole class of detonating gas mixtures.

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INVESTIGATION OF THE SPECIAL CHARACTERISTICS OF THE PROPAGATION AND REFLECTION OF PRESSURE WAVES IN A POROUS MEDIUM

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In view of the wide use of porous materials in technology there arises the need to investigate the dynamic processes taking place in them. The main difference between a porous substance and a solid condensed material is the fact that the condensed phase occupies only part of the volume of the porous medium, which leads to a lowered volumetric density and to a large degree of compressibility. There is particular interest in polymeric media with a small density on the order of 20 kg/m^3, in which up to 98% of the volume is occupied by the gas phase. Such a density is achieved if the medium has a cellular structure of the foam, for example, in polyurethane foam plastics. At the present time, only the elastic properties of polyurethane foam plastics under the action of cyclic [1] and impact [2, 3] loads are known. Questions of the formation of pressure waves in such a medium, with the refraction in it of a shock wave from the gas, of the structure of the wave propagating over the foam plastic, as well as the special characteristics of its reflection from the interface, remain unclear. In the experiments described below, an investigation was made of pressure waves with intensities up to 20 bars in elastic polyurethane foams (PUF) with a porosity of 0.98 and the special characteristics of the reflection of such waves from a rigid wall were also determined.

1. Experimental Unit

The experiments on the study of the structure of pressure waves in a porous medium were made in a shock tube of rectangular cross section 45 • 30 mm, shown in Fig. 1. The high- and low-pressure chambers, denoted by the numbers 1 and 2, have a length of 0.4 and 1.5 m, respectively. The unit is provided with piezoelectric pressure pickups 3-6, with natural frequencies of about 30 kHz. Pickup 3 triggers the scanning of the oscillograph, pickups 4, 5 record the pressure in the passing wave, and pickup 6, that in the reflected wave. The readings of the pickups were recorded in a five-beam Cl-33 oscillograph; the signals of pickups 4 and 5 are fed to channels 1 and 2 (counting the beams from the bottom up), and, of 6, simultaneously to channels 3-5, with different sensitivities.

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