NUMERICAL DETERMINATION OF EFFECT OF EXPLOSIVE DENSITY ON PARAMETERS OF AIR SHOCK WAVES

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The effect of explosive density on parameters of shock waves in air was first studied experimentally in [1] using spherical charges of TEN and lead azide. Numerical calculations of one-dimensional explosive waves in air for standard density were performed in [2-5]. The present study will consider the problem of detonation in air of a spherical TEN charge of variable density.

The one-dimensional system of gasdynamics equations in Lagrangian variables

$$\partial u/\partial t = -1/\rho_0\cdot(r/\lambda)^2\partial p/\partial\lambda,\ \partial r/\partial t = u,$$
$$\partial\varepsilon/\partial t = -p\partial(1/\rho)/\partial t,\ \rho = \rho_0(\lambda/r)^2(\partial\lambda/\partial r) \qquad (1)$$

was solved numerically. Here p, ρ, u, ε are the pressure, density, velocity, and specific internal energy of the gas; t is time; r, λ are the Euler and Lagrange coordinates, related by the expression

$$\lambda = \left(\lambda_0^3 + 3/\rho_0\int_{r_0}^{r}\rho r^2dr\right)^{1/3};$$

the subscript 0 indicates the initial air density and the coordinates of the charge surface.

System (1) is completed by the equation of state of the medium. For air, the equation of state of an ideal gas,

$$p = (k_e - 1)\rho\varepsilon \qquad (2)$$

was used, with effective adiabatic index k_e in the form of an analytical approximation over a wide range of thermodynamic parameters:

$$k_e = \begin{cases} k_0 - 0.042\,(\varepsilon/\varepsilon_k)^2 & \text{for } \varepsilon\leqslant\varepsilon_k, \\ a_k + (1.36 - a_k)\exp(0.223\,(1-\varepsilon/\varepsilon_k)) & \text{for } \varepsilon>\varepsilon_k, \end{cases}$$

where $a_k = 1 + 0.163/(1 - 0.0573\ \ln(\rho/\rho_k))$; $\rho_k = 1.2921$ kg/m³, $\varepsilon_k = 1.116\cdot10^3$ J/kg, $k_0 = 1.402$.

If required, the air temperature can be determined from the thermal equation of state

$$T = p\mu_e/\rho R, \qquad (3)$$

where R is the universal gas constant and μ_e is the effective molecular mass of the air, determined by

$$\mu_e = \begin{cases} 28.96 & \text{for } \varepsilon\leqslant\varepsilon_k, \\ 11.5 + 17.46\exp(0.0445\,(1-\varepsilon/\varepsilon_k)) & \text{for } \varepsilon>\varepsilon_k. \end{cases}$$

For the detonation products, the following binomial equation of state was used [7]:

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 127-131, May-June, 1983. Original article submitted April 26, 1982.

0021-8944/83/2403-0403$07.50

TABLE 1

ρ_{10}, kg/m³	1600	1200	800	400
D, m/sec	7750	6040	4450	3020
$Q\cdot 10^{-6}$, J/kg	5,85	5,65	5,45	5,25
k	2,953	2,80	2,51	1,94
r_0/r_e	0,0137	0,0153	0,0177	0,0226

TABLE 2

ρ_{10}, kg/m³	1600	1200	800	400
r_n/r_0	18,35	17,10	15,28	12,84
η, %	87,30	82,95	81,50	79,30
T_1, °K	11 500	9600	8350	6500
T_2, °K	4 800	4000	3400	2900
K_e	1	1,065	1,110	1,165

$$p = A\rho^n + \gamma\rho\varepsilon, \tag{4}$$

where the constants A, n, γ are determined from the Chapman–Jouguet parameters for detonation of a standard density explosive (single crystal).

Equation of state (4) permits determination of detonation wave parameters in an explosive of arbitrary density with consideration of the change in heat of explosion [8]. In particular, for TEN the calculation results for parameters on the front are approximated well by the expressions

$$\rho_*/\rho_i = 0.053 + 1.28(\rho_{10}/\rho_i), \quad D_*/D_i = 0.225 + 0.775(\rho_{10}/\rho_i)^{1,2},$$

while for the flow region for a spherical wave we have

$$\begin{aligned} \rho_z = u_z = 1 - \left(1 - r_z^{1.15}\right)^{0.5} \quad & \text{for} \quad r_1 \leqslant r \leqslant r_*, \\ u = 0, \ \rho = \rho_i \quad & \text{for} \quad r < r_1, \end{aligned} \tag{5}$$

where $\rho_z = (\rho - \rho_1)/(\rho_* - \rho_1)$; $u_z = u/u_*$; $r_z = (r - r_1)/(r_0 - r_1)$; D is the detonation rate; the subscripts *, 1, 10, i refer to parameters on the detonation front, in the central stationary zone, initial values, and values for a standard density explosive. The radius of the stationary zone and the explosion product density therein are given by

$$r_1/r_* = 0.455 - 0.036(1 - \rho_{10}/\rho_i), \quad \rho_1/\rho_* = 0.646 - 0.348\exp(-3.54(\rho_{10}/\rho_i)).$$

Remaining detonation wave parameters are determined from known relationships on the wave front, and from the detonation products deloading adiabat.

Equation (5) is satisfied by asymptotic solutions in the vicinity of the detonation wave front and weak discontinuity, and is used as initial conditions for numerical solution of the problem of explosion of a spherical TEN charge of variable density.

System (1)-(4) was integrated using an explicit completely conservative difference technique with approximation order $O(h^2 + \tau)$ [9]. Homogeneity is ensured by oblique calculation of the contact discontinuity zone. Thus, to maintain the local approximation upon transition through the contact discontinuity in the detonation product region, a logarithmic grid was used, with cell size decreasing toward the contact discontinuity. Calculation of the shock wave was carried out using the characteristics of system (1) together with dynamic compatibility relationships, ensuring distinction of the strong discontinuity and improving the calculation accuracy. To "diffuse" the internal discontinuities an artificial viscosity was used, introduced by analysis of the differential properties of the solution [10]:

$$q = \delta\rho\Delta r \frac{\partial u}{\partial r}\left(S_1 a + S_2 \Delta r \left|\frac{\partial u}{\partial r}\right|\right),$$

where

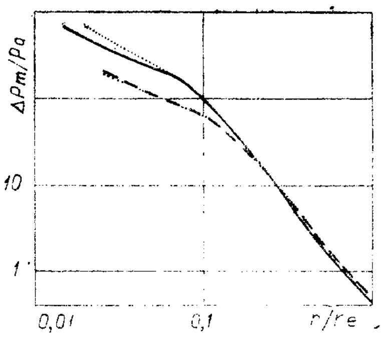

Fig. 1

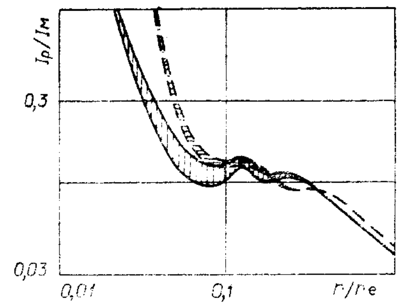

Fig. 2

$$\delta = \begin{cases} 0 \quad \text{for} \quad \dfrac{\partial u}{\partial r} \geqslant 0 \Big\}, & \text{if} \quad \left|\dfrac{\partial^2 u}{\partial r^2}\right| dr - \delta_3 \left|\dfrac{\partial u}{\partial r}\right| \leqslant 0, \\ \begin{matrix}\delta_1 \\ \delta_2\end{matrix} \Big\} \quad \text{for} \quad \dfrac{\partial u}{\partial r} < 0, & \text{if} \quad \left|\dfrac{\partial^2 u}{\partial r^2}\right| dr - \delta_3 \left|\dfrac{\partial u}{\partial r}\right| > 0; \end{cases}$$

a is the speed of sound; S_1, S_2 are coefficients of the linear and quadratic components of the pseudoviscous pressure q; $\delta_1, \delta_2, \delta_3$ are coefficients of the differential analyzer.

Best results were obtained with values $S_1 = 0.25$; $S_2 = 1$; $\delta_1 = \delta_2 = 2$; $\delta_3 = 3$. Calculations were performed on a BÉSM-6 computer with a grid containing 60 nodes in the detonation product zone and 140 nodes in the air shock wave region, at which levels the law of conservation of energy is satisfied within the problem within 0.5%. Calculation time for one variant to a shock wave front radius of $\sim 120 r_0$ at a Courant number of 0.25 was of the order of 5 min.

Calculations were performed for air at a temperature of T = 15°C and TEN charges with densities ρ_{10} = 1600, 1200, 800, 400 kg/m³, with detonation characteristics presented in Table 1 (Q is the specific heat of explosion, k is the adiabatic index on the detonation wave front).

Some calculation results are presented in Figs. 1-4, which show the dependence of excess pressure on the front ΔP_m, excess pressure impulse $Ip = \int_0^\tau \Delta p dt$, velocity head impulse $I_u = \int \frac{\rho u^2}{2} dt$, and duration of compression phase τ on distance r for charges with ρ_{10} = 1600 kg/m³ (solid lines) and ρ_{10} = 400 kg/m³ (dashed lines). Experimental values of Δp_m [1] are shown by the dotted line of Fig. 1. All results are shown in dimensionless form using the scale factors: p_0 = 102,325 Pa; ρ_0 = 1.2249 kg/m³; $u_m = (p_0/\rho_0)^{1/2}$; $r_e = (mQ/p_0)^{1/3}$; $t_m = r_e/u_m$; $I_m = p_0 t_m$. Values of the dimensionless charge radius are presented in the last column of Table 1.

The results for excess pressure on the wave front (Fig. 1) agree well with experimental data. At distances of $r/r_e < 0.3\text{-}0.4$, but also all other shock wave parameters increase with decreasing charge density. Thus, upon change from ρ_{10} = 1600 kg/m³ to ρ_{10} = 400 kg/m³ in the far zone the values of Δp_m, I_u, and I_p increases by 10, 12, and 15%, respectively. The nonmonotonic change of Ip and τ (Figs. 2 and 4) in the range $0.05 < r/r_e < 0.2$ reflects the complex wave character of the flow of the medium, related to formation and propagation of a secondary shock wave. Increase in I_p in the second shock wave is indicated in Fig. 2 by the shaded region.

For the variants calculated, Table 2 presents values of maximum explosion product bubble radius r_b, explosion efficiency η (fraction of energy liberated which is radiated into the air in the first pulsation of the explosion products), and air temperature at the boundary with the explosion products at the initial time T_1 and at the time the bubble reaches its maximum radius T_2.

Despite the fact that the relative size of the gas bubble decreases with decreasing charge density, its absolute size increases, and at ρ_{10} = 400 kg/m³ reaches a value of 20.5 times the radius of a charge with density ρ_{10} = 1600 kg/m³. With decrease in explosive density the explosion efficiency also falls, so that the increase in shock wave parameters

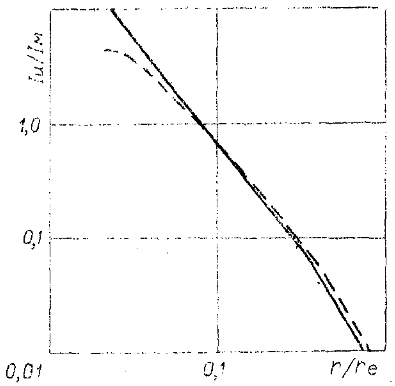

Fig. 3

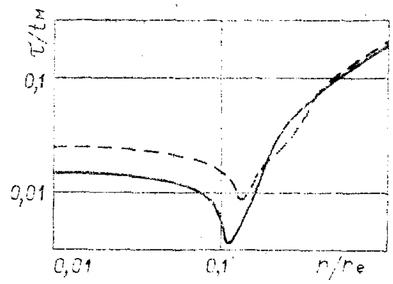

Fig. 4

at large distances can only be explained by a decrease in irreversible losses on the shock wave front. The air temperature on the explosion product contact surface decreases by a factor of 2.2-2.4 during the process of gas bubble expansion.

The falloff in air shock wave parameters in the region $r/r_e > 0.55$ ($\Delta p_m < 2p_0$) is practically the same for any charge density, making it possible to introduce an energy equivalent relative to a standard density charge K_e, values of which are presented in Table 2. The relationship of K_e to explosive density in the range 400 kg/m³ $\leqslant \rho_{10} \leqslant$ 1600 kg/m³ is approximated well by the linear expression

$$K_e = 1 + 0.1376(1.6 - \rho_{10}/1000). \tag{6}$$

In the range $2 < \Delta p_m/p_0 \leq 10$ the value of K_e depends not only on explosive density, but also on shock-wave intensity, obeying the law

$$K_e = 1 + 0.0172(10 - \Delta p_m/p_0)(1.6 - \rho_{10}/1000). \tag{7}$$

Introduction of the energy equivalent K_e permits use of the same expressions for air shock-wave parameters over the range $\Delta p_m < 10p_0$ for charges of various densities. Calculations for other solid explosives indicate that Eqs. (6), (7) are applicable within ∿1%.

Thus, the binomial equation of state for detonation products and the simplest approximation for the thermodynamic properties of air permit satisfactory consideration of explosive density in calculating the parameters of air shock waves.

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