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NUMERICAL SIMULATION OF PROCESSES IN A SPHERICAL COMBUSTION CHAMBER

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A theoretical model of gasdynamic and mechanical processes in a spherical explosion chamber is considered. Comparison of numerical results obtained with this model with calculated and experimental results of other authors shows good agreement.

The present study will describe a method for numerical simulation of the processes which take place in a spherical explosion chamber by using the equations of the mechanics of continuous media without consideration of the differing natures of dissipative effects (radiant diffusion, turbulence, etc.) which can play a significant role in real conditions. The model to be considered permits description of both gasdynamic processes within a chamber caused by expulsion and braking of material from the energy source, and elastic compression waves — expansion of the medium under dynamic loading of the chamber walls at stresses not exceeding the strength of the wall material, i.e., for situations of practical interest [1, 2].

The proposed model was used to study processes in an explosion chamber which consisted of three spherically symmetric regions: 1) a central region 3 cm in diameter (energy source) with density $\rho_1 = 2.7$ g/cm^3 and mass $3.054 \cdot 10^2$ g, within which an energy of $E_0 = 7.106 \cdot 10^9$ J is liberated instantaneously corresponding to a specific internal energy of $E = 2.327 \cdot 10^7$ J/g; 2) an air layer of thickness ~ 2 m with gas density $\rho_0 = 1.293 \cdot 10^{-3}$ g/cm^3 and pressure $P_0 = 1$ atm; 3) a medium surrounding the air cavity (aluminum with density of $\rho_1 = 2.7$ g/cm^3 was chosen for the chamber wall material).

Since the problem under study allows similarity transformation of the linear R_* and time t_* scales with the relationships $R_* \sim E_0^{1/3}$ and $t_* \sim E_0^{1/3}$, some of the results obtained were compared with data of [2] for an explosion of energy $E_0 = 7.106 \cdot 10^{12}$ J in an air cavity of radius $R_0 = 20$ m.

The thermodynamic parameters of the air layer were calculated with a tabular equation of state $P = P(E, \rho)$, obtained by linear interpolation in logarithmic variables using the data of [3]. The media in the first and third regions were described by Tillotson's equations [4-6], which are recommended for calculation of high-velocity shocks on metal and plastic targets [5], which corresponds to real conditions on the chamber walls. The well-known equations of [7, 8], which relate deformation and stresses produced by action of shock wave pulses on the chamber walls, were used to consider the mechanical properties of the surrounding medium (chamber walls).

In describing wave motion in the chamber and walls, strength and other inelastic phenomena, nonequilibrium properties, and radiation characteristics of the medium will be neglected, which, according to [2], is completely justifiable.

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It follows from numerical calculations that in the given case, just as in [2], the effect of the elastic reaction of the walls on the dynamics of motion within the chamber may be neglected. This is possible because of the relatively small changes in chamber volume. In the variant studied the chamber radius increased over a period of several milliseconds, i.e., in the most intense stage of the process, only by ∿ 0.1 cm (0.05%). It should be noted that even with elastic reaction of the wall and small deformations of the medium, the question of the effect of cracks and fractures in the wall material remains open. A significant piece of evidence indicating that such effects may be neglected is the significantly more inertial character of such processes as compared to shock-wave motion in the chamber in the initial definitive stage of the process. Moreover, in the example studied, the corresponding destruction criteria were greater than the elastic stresses developed in the chamber walls. As was noted in [2], the most significant deviation from results obtained with neglect of the destructive action of gasdynamic processes within the chamber on the walls is that fusion or evaporation of the wall material may occur. However, for consideration of these effects data on radiation fluxes in the chamber and walls are necessary, which is a problem in itself. The approximation to be considered herein also ignores the effect of vapors of the energy source material in determining dynamic loads on the chamber walls, since in the example studied the vapors did not expand beyond one half of the chamber radius. At the same time, it should be kept in mind that under real conditions a definite role may be played by turbulent mixing of source vapors with the air in the chamber. However, this effect is not considered in the present model and has not been studied in the literature.

Processes in the explosion chamber were calculated with the system of gasdynamic equations presented below in Lagrangian form for a multiregion medium with specified thermodynamic and elastoplastic properties in the one-dimensional spherically symmetric case [4-9]:

equation of motion

$$\dot{R} = U,\ \dot{U} = V_0 \left[\frac{R}{M}\right]^2 \frac{\partial \Sigma_R}{\partial M} + 2\,\frac{\Sigma_R - \Sigma_\theta}{R},$$

where $\Sigma_R = -(P + q) + s_1$; $\Sigma_\theta = -(P + q) + s_2$,

continuity equation

$$V = V_0 \left[\frac{R}{M}\right]^2 \frac{\partial R}{\partial M},$$

energy equation

$$\dot{E} = V(s_1\dot{\varepsilon}_1 + 2s_2\dot{\varepsilon}_2) - (P + q)\dot{V},$$

stress deviators

$$\dot{s}_1 = 2\mu_1\left(\dot{\varepsilon}_1 - \frac{1}{3}\frac{\dot{V}}{V}\right),\quad \dot{s}_2 = 2\mu_1\left(\dot{\varepsilon}_2 - \frac{1}{3}\frac{\dot{V}}{V}\right),\quad \dot{s}_3 = (\dot{s}_1 + \dot{s}_2),$$

deformation rates

$$\dot{\varepsilon}_1 = \frac{\partial U}{\partial R},\quad \dot{\varepsilon}_2 = \frac{U}{R},\quad \dot{\varepsilon}_3 = \dot{\varepsilon}_2,$$

Mays' creep condition

$$s_1^2 + s_2^2 + s_3^2 \leqslant \frac{2}{3}\,Y_0^2,$$

Tillotson's equations

$$P = [a + b/(E/c\eta^2 + 1)]\,E\rho + A\mu + B\mu^2,\quad \rho \geqslant \rho_1,\ \mu = \eta - 1,\ \eta = \rho/\rho_1,$$

$$P = aE\rho + [bE\rho/(E/c\eta^2 + 1) + A\mu\exp\left(-\beta\left(\frac{1}{\eta} - 1\right)\right)]\exp\left(-\alpha\left(\frac{1}{\eta} - 1\right)^2\right),\quad \rho < \rho_1.$$

A dot above a quantity in the equations indicates the time derivative along the trajectory of a particle of the medium. Using characteristic values for the problem – time $t_* = 10^{-5}$ sec, length $R_* = 1$ cm, pressure $P_* = 2.7 \cdot 10^4$ atm, density $\rho_* = 27$ g/cm^3, internal energy $E_* = 10^3$ J/g, the system of equations was reduced to a dimensionless finite-difference form

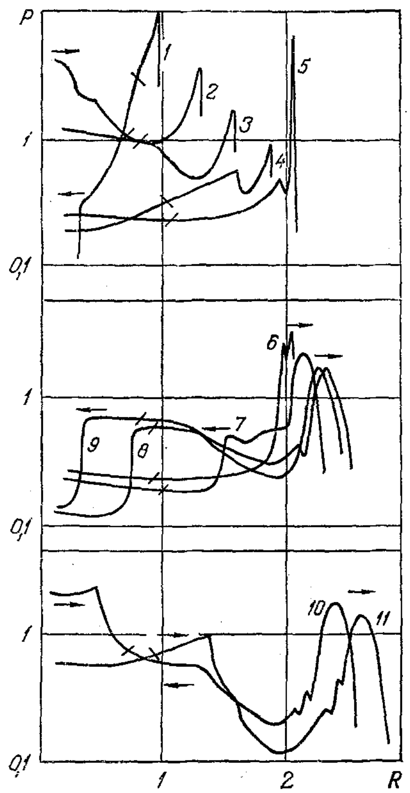

Fig. 1. Distribution of pressure P (kbar) in chamber along radial coordinate R (m) for various times t (msec): 0.0108 (1), 0.0252 (2), 0.043 (3), 0.0682 (4), 0.0926 (5), 0.1 (6), 0.132 (7), 0.155 (8), 0.162 (9), 0.174 (10), 0.214 (11). Mark on curve indicates position of contact surface between gaseous source products and air layer in chamber. Arrows indicate direction of motion.

[7, 9]. Numerical calculations were performed on an ES-1055 computer. The computation time for one oscillation of pressure (density, temperature) on the chamber walls for a calculation grid of 100 cells comprised ∿ 40-50 min.

Figures 1-3 show results of the numerical study of wave processes in the spherical explosion chamber considered.

The shock wave formed by intense energy liberation in the central region moves toward the chamber walls, reaching them at a time $t \simeq 0.0926$ msec (Fig. 1). The vapors of the source material form their own shock front, which overtakes the main wave after the latter is reflected to the center, and the process of shock wave reflection from the chamber walls becomes more complicated. This is because of the presence of double maxima in pressure and density at the peak times (Fig. 2). The absence of double maxima in the analogous calculations of [2] can be explained by doubling of the spatial cells after the first several maxima, which introduces additional uncertainty into the numerical calculations, so that significant details are lost from subsequent results. However, despite some qualitative difference, there is good correspondence between the results of [2] and the present study for both the first shock pulses on the wall, and the mean parameter values in higher-order pulses.

As follows from the curves presented in Fig. 2, the change in thermodynamic parameters on the walls is of an impulsive periodic character. With the passage of time a certain frequency of shock-wave oscillation is established in the chamber, equal to ∿4 kHz (∿400 Hz in [2]). After the first several pulses the pressure and density on the chamber walls fall off quite rapidly and then oscillate with constant amplitude about mean values equal to ∿400 bar and $\sim 2\ \rho_0$.

The weakly damped character of the wave processes in the explosion chamber is due to the fact that there is little transfer to the chamber walls. Numerical calculations revealed

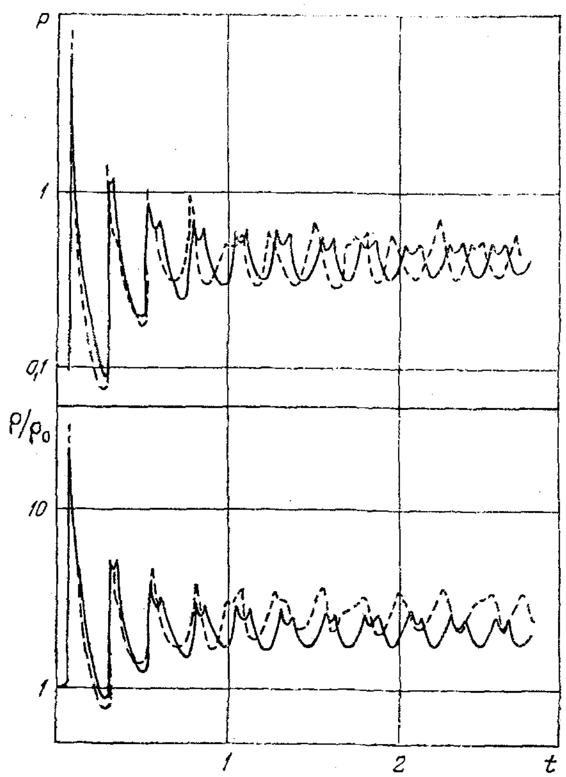

Fig. 2. Pressure P (kbar) and relative density ρ/ρ_0 on chamber walls vs time t (msec). Dashed curve is results of [2].

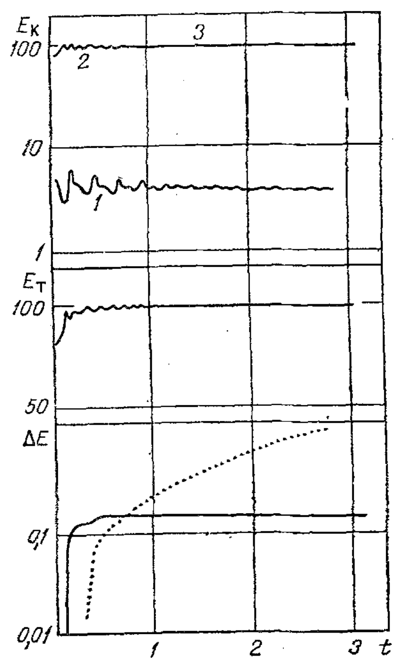

Fig. 3. Distributions of chamber energy E_C (%) over regions [1) source; 2) air layer; 3) walls], chamber energy transferred to walls, ΔE (%) (dashed line is hydrodynamic model of medium; solid line, elastoplastic), and thermal component E_T (%) of chamber energy versus time t (msec).

that the fraction of energy ΔE transmitted through the chamber walls by the elastic pulses generated within is in the limit only ~0.15% (Fig. 3), which agrees well with the conclusions presented in [1, 10].

It is evident from Fig. 3 that the limiting value of energy radiated by the chamber is already acheived at the very start of the process, when the amplitude of the shock waves acting on the wall is maximal.

The curves of Fig. 3 show that practically all the energy within the chamber is thermal in nature, and as a result of energy redistribution within the chamber the air layer receives ~96% and the gaseous source products ~4% of the total energy. In the end the energy source is transformed into a ring-shaped spherical air layer ~1 m thick (about 10 m in [2]), with the behavior of pressure and other parameters on the boundary thereon being of a periodic oscillatory character defined by wave processes within the chamber.

In conclusion, we note that the results obtained for the energy ΔE transferred to the chamber walls depends to a significant extent on the physical model of the medium, and are most reliable when the elastoplastic properties of the wall material are considered. As an illustration of the dependence of ΔE on the model chosen, Fig. 3 presents results from an analogous version of the problem using the hydrodynamic model. It is evident that the process of energy transfer to the chamber walls for the two cases is both quantitatively and qualitatively different.

NOTATION

ρ, density; E, specific internal energy; E_C, chamber energy; ΔE, chamber energy transferred to walls; E_T, thermal component of chamber energy; R, radial coordinate; t, time; U, velocity; P, pressure; q, pseudoviscosity; M, mass (Lagrangian) coordinate; V, specific volume; Σ_R and Σ_θ, radial and tangential stresses; s, stress deviator; s_1, s_2, s_3, components of the stress deviator; ε, deformation vector; ε_1, ε_2, ε_3, components of deformation vector; ρ_0, density of air; ρ_1, density of source and chamber wall material; $\Delta\rho$, relative density change in chamber walls; E_0, source energy; R_0, air cavity radius; μ_1, shear modulus; Y_0, yield limit; A, B, a, b, c, α, β, constants in equation of state; R_*, t_*, P_*, ρ_*, E_*, characteristic parameter values.

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