Hydrodynamics of Explosion: Models and Software for Modeling Explosions and Estimation of Their Consequences

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Abstract

Physical and hydrodynamic processes accompanying explosions of condensed explosives and fuel-air mixtures have been considered. Wide-range equations of the state of explosion products and air have been derived. A physical model and a program code have been developed for modeling one-dimensional hydrodynamics of explosion. This firmware forms the basis for estimation of explosion consequences.

1 Hydrodynamics of Explosion

Sharply expanding gaseous products of explosion act as a piston on the surrounding medium, where forms a shock wave (SW), in the front of which the initially cold air is compressed and heated. The pressure in SW in the vicinity of explosion can reach $\sim 10^2 - 10^3$ atm. A shock wave propagates from the epicenter of explosion at a velocity exceeding the velocity of sound in an undisturbed air. The energy of explosion products (EP) during their expansion is transferred to the outer region and changes to thermal and kinetic energy of the surrounding gas.

At early stages of shock wave propagation (in the near zone of explosion) the pressure behind the wave front is much higher than the pressure of the outer medium. This stage of explosion is called *strong explosion* [1]. Here, the explosion parameters are described by a simpler analytical method since the self-similar model is realized [2]. The velocity of SW at this stage can reach ≥10 km/s. Shock wave decelerates with time, the values of pressure, velocity, and density in the SW decreases. At this intermediate *hydrodynamic* stage the velocity of SW motion is $\sim 1-10$ km/s. Overpressure and its pulse are rather large here to cause tangible destruction.

At subsequent time instances, due to dissipation of explosion energy in a large volume the SW amplitude decreases, the overpressure behind the front is not large, and the velocity of SW propagation, tends to the velocity of sound in air. In this phase, kinetic energy of directed motion of substance decreases thus changing to thermal energy. This late stage of explosion describes the behavior of a weak compression wave, and can be considered on the basis of the laws of acoustics [3].

Shock wave is the main factor of the effect of explosion on the surrounding medium and different objects. The shock wave propagating at a supersonic velocity with a sharp pressure jump and

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high compression of air exerts a pulse effect on the objects. This effect is due to both the overpressure in SW and a projectile action (velocity pressure) of SW caused by air motion. Both factors lead to the so-called pulse loading of the object. If the object is in the near zone of explosion, it is subject to fragmentation and strong plastic deformation. At a distance from the explosive charge destructions are, naturally, less intense, but the zone where they occur is much larger.

2 Equations of State of Explosion Products and Environment

For hydrodynamic description of explosion processes – requires the knowledge of the equation of state of substance. In modeling the dynamics of explosion different equations of state (EOS) of explosion products were used. One of them is the Kuznetsov – Shvedov (KS) EOS for the products of detonation of cyclonite [4]. Another widely spread caloric EOS is the Jones – Wilkins – Lee equation of state [5, 6]. The caloric EOS KS $p = p(\varepsilon,\rho)$ is shown in Fig. 1. The numbers at the curves indicate densities of the explosion products (in g/cm^3). In the caloric EOS with the cold term, the value of p (the sum of thermal and cold pressures), stops to depend on ε at rather large ρ. Thus, at a specific value of ρ the value of ε cannot be lower than cold energy $\varepsilon_{cold}(\rho)$. The range of inaccessible parameters is bounded from the right by the curve of cold compression (dashed line in Fig. 1).
The mole fractions of air are $0.7812\,N_2 + 0.2095\,O_2 + 0.0093\,Ar$ .The thermodynamic characteristics of air are determined by taken into account dissociation of molecules and ionization of atoms. In this case, we can use the EOS of an ideal gas $\varepsilon = p / [\rho(\gamma - 1)]$ with effective adiabatic index $\gamma = \gamma_{ef}(p,\rho)$ [7]. In Fig. 2 the dependence $\gamma_{ef}(p,\rho) - 1$ is shown.

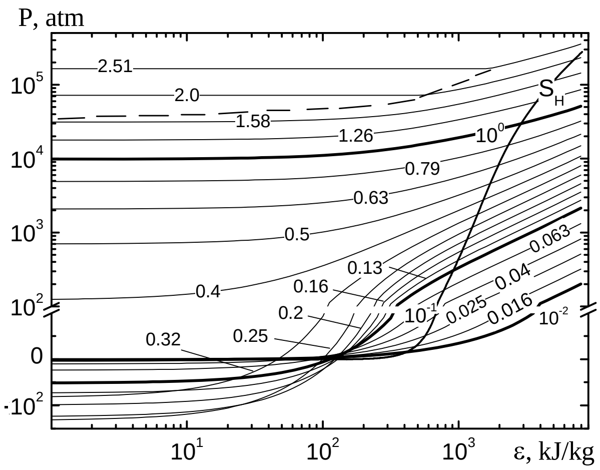

Figure 1. The equation of state of the EP

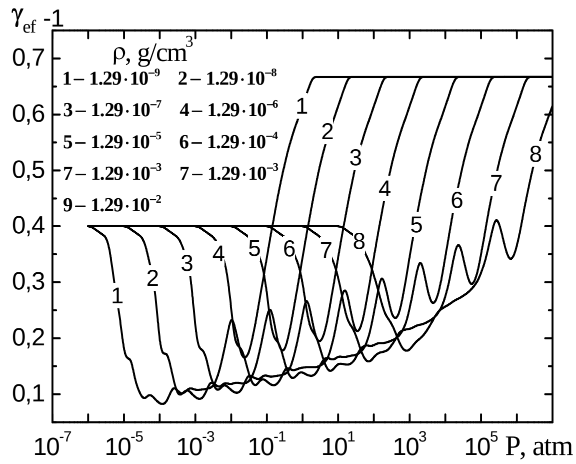

Figure 2. Dependence ($\gamma_{ef} - 1$) from p and ρ

3 The Solution of the Gas Dynamics Equations

Numerical methods of the continuum mechanics form the basis for mathematical simulation of explosion processes. The motion is described by the system of gas dynamics equations that express the laws of conservation of mass, momentum, and energy. In a general one-dimensional formulation it is convenient to use the Lagrangian system of coordinates. The corresponding equations have the form:

$$u = \frac{\partial r}{\partial t}, \qquad \rho = \frac{\partial m}{r^{\nu-1}\partial r}, \qquad \frac{\partial u}{\partial t} + r^{\nu-1}\frac{\partial p}{\partial m} = 0, \qquad \frac{\partial \varepsilon}{\partial t} + p\frac{\partial (r^{\nu-1}u)}{\partial m} = 0. \tag{1}$$

Here the Lagrangian coordinate m represents the mass of substance contained in a unit solid angle, r is the Eulerian coordinate, t is the time, u is the velocity, ε is the specific internal energy, ν is the symmetry factor. This system of equations (with EOS) is complete if the initial and boundary conditions are specified. Since the process of detonation of explosive in modeling the dynamics of explosion was not considered, as initial condition we specified the parameters of the products of explosion in the state corresponding to instantaneous explosion energy released in them and the outer medium (air) were taken to be undisturbed. Thus, the initial problem is formulated as the problem of decay of discontinuity.

To solve equations (1) we use a fully conservative difference scheme of the second order of accuracy [8] used by the authors of the software EXPLOSION as the basis [9].

4 Estimation of the Effect of the Explosive Shock Wave

Based on numerical modeling of explosions of condensed explosives (cyclonite, trotyl, etc.) and fuel-air mixtures (ethylene oxide) we can find the dependence of overpressure in the shock wave on the energy of explosion and the distance to its epicenter. This dependence is presented in Fig. 3. Overpressure in both free-falling SW and reflected wave are shown as function of scaled distance. The distance is obtained by multiplying r by the cube root of the mass of the TNT equivalent of explosion. For a falling SW in air at normal pressure $p_0 = 1$ atm these results can be presented in the form

$$r_F(m) = C(\Delta p_F(atm))E^{1/3}(kg\,TNT), \quad C = a + b(\Delta p_F)^{-\delta}. \tag{2}$$

For the above-considered explosions of explosives we have

$$E:\ a = 0.624, b = 1.814, \delta = 0.632;\ \ FAM:\ a = 0.509, b = 1.582, \delta = 0.69. \tag{3}$$

These relations hold within the most interesting range of overpressures $0.05 \le \Delta p_F \le 1.5$ atm. When $\Delta p_F < 0.05$ atm SW is weak and doest not substantially affect the outer medium. The region $\Delta p_F > 1.5$ atm is the zone of complete destruction, fatal for people.

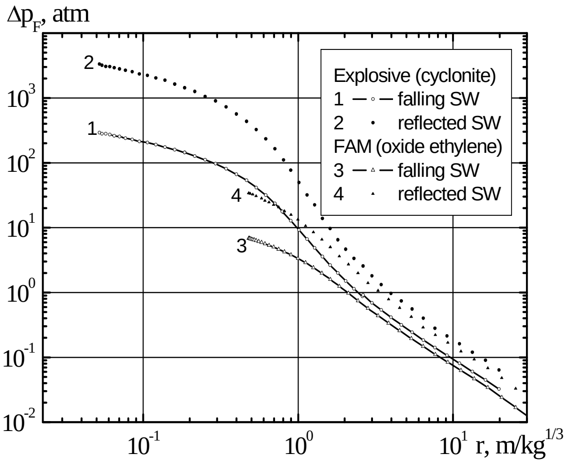

Figure 3. Excess pressure in falling and reflected SW as a function of distance and energy of explosion.

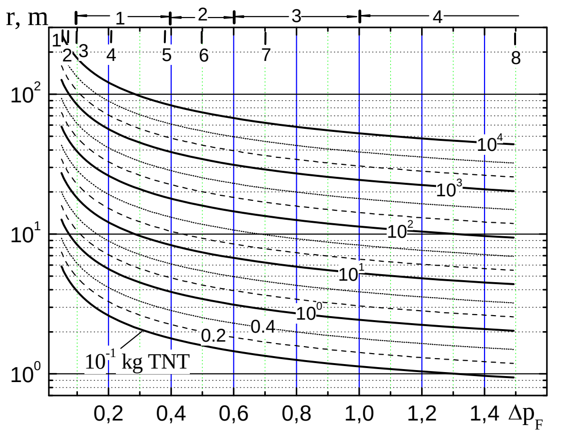

Figure 4. Dependence of the type of injuries and characters of destructions on the energy of explosion for condensed explosives and the distance to its epicenter (Δp_F in atm). Ranges 1-4 refer to the typical human injuries , 1-8 indicate the zones of destruction under the effect of SW.

Expressions (2) and (3) relate implicitly the overpressure with the energy of explosion and the distance to its epicenter. However, they can be recalculated such that the dependence $\Delta p_F(E, r_F)$ was found in the explicit form. If these data are compared with the existing criteria of different traumas in people and destructions of structures and buildings of the infrastructure, then we can approximately imagine the consequences of explosion effects on people and the surrounding medium. In most mainly medicinal and military-engineering sources the character of traumas and destructions are related to overpressure in the explosive wave. In a generalized form these data are presented in Tables 1, 2. With account for the presented criteria, Fig. 4 shows the ranges of distances and energies of explosion causing the respective consequences.

Table 1: Dependence of Typical Injuries on the Overpressure in SW

No	Type of injury	Characteristic features	Δp_F , atm
1	Minor injury	Bruises, contusions, displacements	0.1–0.4
2	Moderate injury	Brain contusion, bleeding, orthopedic injuries	0.4–0.6
3	Severe injury	Fractures, loss of consciousness, internal injuries	0.5–1.0
4	Fatal termination		> 1.0

Table 2: Relationship between Typical Destruction and the Overpressure in SW

No	Type of destruction	Δp_F ,atm
1	Destruction of glazing	0.05
2	Windows and doors are forced out	0.07
3	Severe destruction of least reliable constructions	0.10
4	Destruction of residential buildings	0.21
5	Severe destruction of buildings made of cast-in-situ reinforced concrete	0.38
6	Complete destruction of buildings	0.50
7	Destruction of extra high durable concrete constructions	0.70
8	Destruction of special shelters	1.50

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