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Thermal radiation of explosion: estimations of risk of thermal defeat of people and occurrence of fires

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ABSTRACT

Physical and hydrodynamic processes, accompanying explosions of condensed explosives and fuel-air mixtures are considered. The physical model, algorithm, and program code for modeling one-dimensional hydrodynamic processes, which are based on the equations of gas dynamics in the Lagrangian presentation, are discussed. The results of multiple systematic calculations of the dynamics of explosion are presented. These results have allowed in details to describe the spatial-temporal pattern of flow, the process of the energy transfer from explosion products to the surrounding medium, formation, propagation, and decay of a shock wave. The obtained results are compared with the approximation of a strong point explosion, theoretical and experimental literature data. The developed model and program code showed high efficiency and operability within a wide range of explosion parameters and conditions of the outer medium.

KEYWORDS: Explosion, Shock wave, Equation of state, Numerical modeling, Similarity laws, Explosion products.

Introduction

Explosion is a process of very fast chemical or physical conversion of substance, which is accompanied by transition of its internal energy to mechanical work. The work executed during explosion is related to fast expansion of the explosion products (EP) – compressed gases and vapors – which have been formed in a large amount. A most important feature of explosion is the formation of a shock wave (SW), i.e., a sharp pressure jump. A shock wave propagates in the environment and is a direct cause of the destructive action of explosion [1, 2]. Sharply expanding gaseous products of explosion act as a piston on the surrounding medium where there forms a shock wave, in the front of which the initially cold air is strongly compressed and heated. The pressure in SW in the vicinity of explosion can reach $\sim 10^2 - 10^3$ bar. A shock wave propagates from the epicenter of explosion at a velocity exceeding the velocity of sound in an undisturbed medium. In this case, even new volumes of the surrounding medium are involved in motion. The energy of explosion products 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, which usually is close to atmospheric pressure. This stage of explosion is called *strong explosion* [3]. Thus, backpressure of the outer medium can be disregarded in the near zone. Here, the explosion pattern is described by a simpler analytical method since the so-called self-similar mode is realized. The velocity of SW motion at this stage can reach ≥10 km/s. Shock wave decays with time, the values of the pressure jump, velocity, and density in the SW front decrease. At this intermediate *hydrodynamic* stage the pressure drop in the wave front is comparable with the outer medium pressure, the density of compressed substance behind the SW front exceeds the density in the undisturbed state several fold, and the velocity of SW motion is $\sim 1-10$ km/s. Excess pressure 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 pressure excess behind the front over atmospheric pressure is not large, and the velocity of SW propagation, while decreasing, tends to the velocity of sound in the surrounding medium. In this phase, kinetic energy of directed motion of substance in the region of explosion decreases thus changing to thermal energy. This late stage of explosion describes the behavior of the outer medium at large distances from the region of energy release where propagation of a weak compression wave, into which SW is degenerated, can be considered on the basis of the laws of acoustics. In this so-called region of *weak explosion* the asymptotic laws of the behavior of hydrodynamic characteristics of a weak shock wave are valid.

Shock wave is the main factor of the effect of explosion on the surrounding medium and different objects. The shock wave front (SWF) propagating at a supersonic velocity with a sharp pressure jump and high compression of air exerts a pulse

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effect on the objects that are within the region of explosion. This effect is due to both the excess pressure 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.

Explosive Waves from the Point Source

The full set of the parameters characterizing a strong point explosion includes its energy E, density of the surrounding gas ρ_0, spatial coordinate r reckoned from the center (axis or plane) of explosion, and time t from the instant of energy release. We note that E is the energy of explosion for a spherical case. In the cylindrical geometry, E is the energy related to the length unit of the explosion source, whereas in the plane geometry – to the unit of its surface. The symmetry of problem is determined by the parameter ν with its values 1, 2 and 3 corresponding to the plane, cylindrical, and spherical cases, respectively. The dimensions of the problem parameters are: $[E] = \mathrm{J}/\mathrm{m}^{3-\nu}$, $[\rho_0] = \mathrm{kg}/\mathrm{m}^3$, $[r] = \mathrm{m}$, $[t] = \mathrm{s}$, and the only dimensionless combination of r, t, E, ρ_0 is

$$\lambda = \frac{r}{\left(E/\rho_0\right)^{1/(\nu+2)} t^{2/(\nu+2)}}. \tag{1}$$

Hence it follows that the coordinate of the SWF, denoted as r_F is

$$r_F = \alpha\left(E/\rho_0\right)^{1/(\nu+2)} t^{2/(\nu+2)}. \tag{2}$$

In (2), the coefficient α is found from the law of energy conservation

$$E = \sigma_\nu \int_0^{r_F} \left(\rho\varepsilon + \rho u^2/2\right) r^{\nu-1} dr, \tag{3}$$

which expresses the fact that the energy E, which was initially accumulated in explosive products, being transferred to the environment during the development of the explosion, is conserved and consists of thermal and kinetic energy of the gas involved in motion. Differentiating the dependence of the SWF coordinate on time we immediately find the velocity of SW propagation D as function of time or space coordinate:

$$D = \frac{dr_F}{dt} = \frac{2\alpha}{\nu+2}\left(E/\rho_0\right)^{1/(\nu+2)} t^{-\nu/(\nu+2)}, \qquad D = \frac{2}{\nu+2}\alpha^{(\nu+2)/2}\left(E/\rho_0\right)^{1/2} r_F^{-\nu/2}. \tag{4}$$

In a strong SW, gas with an initial density ρ_0 is compressed to a maximum possible degree, which is determined by the value of its γ

$$\rho_F = \frac{\gamma+1}{\gamma-1}\rho_0. \tag{5}$$

The pressure on SWF is related to the velocity of SW motion through the gas $p_F = 2\rho_0 D^2/(\gamma+1)$ and we immediately find the dependence of pressure on SWF on time or SW coordinate

$$p_F = \frac{2}{\gamma+1}\left(\frac{2\alpha}{\nu+2}\right)^2\left(\frac{E}{\rho_0^{\nu/2}}\right)^{2/(\nu+2)} t^{-2\nu/(\nu+2)}, \qquad p_F = \frac{2\alpha^{(\nu+2)}E}{\gamma+1}\left(\frac{2}{\nu+2}\right)^2 r_F^{-\nu}. \tag{6}$$

Thus, in order the explosion phenomenon could be referred to the class of a strong point explosion and described by relations (1) – (6), the mass of gas involved in motion and the size of the region covered by motion must greatly exceed the mass of the explosion products M_{EP} and their initial typical size r_{EP}. At the same time, initial concentration of energy in the explosion products must be so high that during some period of time the pressure on the front of the propagating SW greatly exceeded the pressure in the surrounding gas. Since these two conditions are mutually contradicting, approximation of a strong point explosion is the so-called intermediate asymptotes. It can hold at that stage of the process when the information about the source parameters M_{EP} and r_{EP} has been already "forgotten" and the explosion "remembers" only a value of energy E and the relation $p_F >> p_0$ still holds. For many real explosions such conditions are not met simultaneously. In this case, self-similar asymptotes are absent. However, with very high volumetric concentration of energy (e.g., nuclear explosion or powerful trotyl explosions) these conditions hold simultaneously within a certain time interval.

Similarity Laws of Explosions

As SW decays, the pressure of the outer medium p_0 begins to play role, the explosion transfers to the stage when back pressure must be taken into account. New parameters of length R_0, velocity, c_0, and time t_0 :

$$R_0 = \left(E / p_0\right)^{1/\nu}, \qquad c_0 = \left(p_0 / \rho_0\right)^{1/2}, \qquad t_0 = R_0 / c_0 = E^{1/\nu} p_0^{-(\nu+2)/2\nu} \rho_0^{1/2}. \tag{7}$$

The quantity R_0 is the dynamic radius of explosion. According to (7), R_0 determines the characteristic size of the region where the internal energy of the surrounding medium which is close to $p_0 R_0^{\nu}$ turns to be equal to the explosion energy E. The constant with the dimensionality of the velocity c_0 agrees within $\gamma^{1/2}$ with the velocity of sound in the undisturbed medium. The time scale t_0 is the time during which sound disturbance passes the region of size R_0. If we introduce the dimensionless parameters of SW which are obtained from division of their dimensional values by the corresponding scaling quantities

$$\bar{r}_F = r_F / R_0, \qquad \bar{t} = t / t_0, \qquad \bar{D} = D / c_0, \qquad \bar{p}_F = p_F / p_0, \tag{8}$$

in the dimensionless form the law of propagation of a strong SW is

$$\bar{r}_F = \alpha \bar{t}^{\,2/(\nu+2)}, \quad \bar{D} = \frac{2\alpha}{\nu+2} \bar{t}^{\,-\nu/(\nu+2)}, \quad \bar{p}_F = \frac{2}{\gamma+1}\left(\frac{2\alpha}{\nu+2}\right)^2 \bar{t}^{\,-2\nu/(\nu+2)}. \tag{9}$$

It is seen that the parameters of explosion – its energy E and the density of the surrounding medium ρ_0 – are absent in such presentation, i.e., explosions with different values of these parameters are described by a universal dependence (9). The law (9) sets similarity of strong explosions with different values of energy: if two charges are exploded in the same atmosphere, then at the same reduced instant of time they have the same reduced coordinate of the wave front. Under the same conditions two explosions have the same velocity of SW $\bar{D}$ and the same pressure $\bar{p}_F$ at the same reduced instant of time $\bar{t}$ or at the same reduced distance $\bar{r}_F$. It is important to note that that similarity laws, though in an approximate form, hold also at a later stage which does not satisfy the conditions of a strong point explosion. This principle forms the basis for prediction of the parameters of full-scale explosive waves by the parameters of explosions conducted under experimental conditions (the Hopkinson-Cranz method) [2].

Algorithm for solving the gas dynamics equations

Numerical methods of the continuum mechanics form the basis for mathematical simulation of explosion processes. The motion of the medium under the action of the explosion is described by the system of gas dynamics equations that express the laws of conservation of mass, momentum, and energy. In a one-dimensional formulation it is convenient to use the Lagrangian system of coordinates where the corresponding equations have the form [5]:

$$u = \frac{\partial r}{\partial t}, \qquad \rho = \frac{\partial m}{r^{\nu-1}\partial r}, \qquad \frac{\partial u}{\partial t} + r^{\nu-1}\frac{\partial p}{\partial m} = 0, \qquad \frac{\partial \varepsilon}{\partial t} + p\frac{\partial (r^{\nu-1}u)}{\partial m} = 0. \tag{10}$$

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 mass velocity, ε is the specific internal energy, the quantity $\partial / \partial t$ is the substantive time derivative, ν is the symmetry factor. The first equation in the system of equations (10) is the definition of velocity, the second equation connects the Lagrangian coordinate with the spatial variable (continuity equation), the third equation is the equation of motion, and the last one is the equation of energy. The system of equations (10) is supplemented by initial and boundary conditions. Hydrodynamic equations appear closed by the equation of state describing the thermodynamic properties of matter. A detailed description of the method of solving equations (10) with initial and boundary conditions is given in [5]. It also contains the results of testing the developed software. Hydrodynamic parameters near the epicenter of explosion time instants t < 3.2*10E-4 s are shown in figure 1.

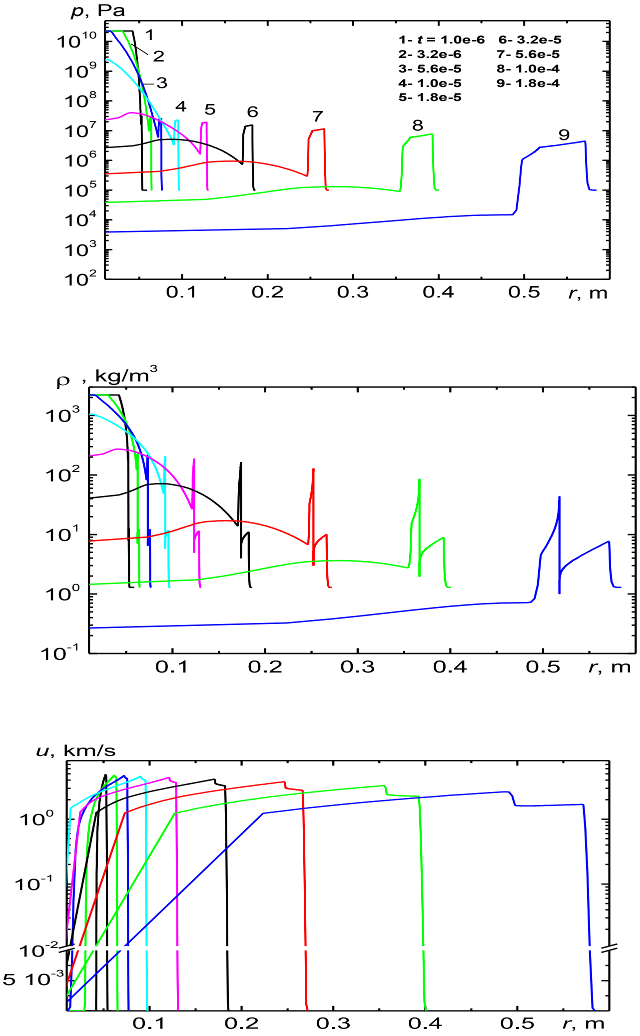

Figure 1. Hydrodynamic parameters near the epicenter of explosion time instants t < 3.2* 10E-4 s

Estimation of the effect of the blast waves on environment

Based on numerical modeling of explosions of condensed explosives (cyclonite, trotyl, etc.) and fuel-air mixtures (ethylene oxide) we can find the dependence of excess pressure in the shock wave on the energy of explosion and the distance to its epicenter. This dependence is presented in Fig. 2. Excess pressure in both free-passing (falling) SW and reflected wave are shown, the reduced distance is plotted on the abscissa axis. The distance (in meters) 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 $p_0 = 1$ bar (10^5 Pa) these results can be presented in the form

$$\begin{aligned} r_F(\mathrm{m}) &= C(\Delta p_F(\mathrm{bar}))\, E^{1/3}(\mathrm{kg\,TNT}), \\ C &= a + b(\Delta p_F)^{-\delta}. \end{aligned} \qquad (11)$$

For the explosives (E) and fuel-air mixtures (FAM) we have

$$
\begin{aligned}
&\text{E: } a = 0.624,\ b = 1.814,\ \delta = 0.632; \\
&\text{FAM: } a = 0.509,\ b = 1.582,\ \delta = 0.69.
\end{aligned}
\tag{12}
$$

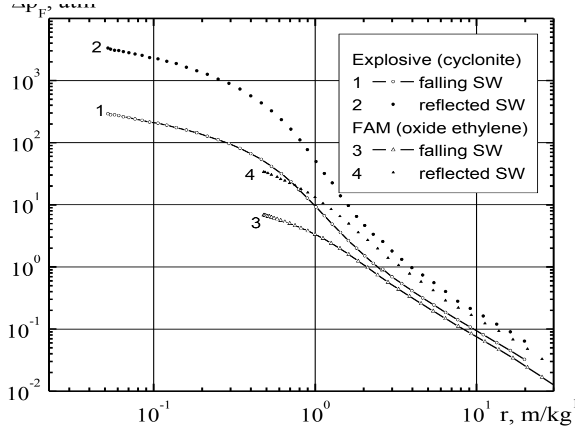

Figure 2. Excess pressure in falling and reflected SW as a function of distance and energy of explosion [5]

These relations hold within the most interesting range of excess pressures ($0.05 \le \Delta p_F(\text{bar}) \le 1.5$ bar. When $\Delta p_F < 0.05$ bar shock wave is weak and does not substantially affect the outer medium. The region $\Delta p_F >$ 1.5 bar is the zone of complete destruction, fatal for people.

Expressions (11) and (12) relate implicitly the excess pressure 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 excess pressure in the explosive wave. In a generalized form these data are presented in Tables 1 and 2.

Table 1. Dependence of typical injuries on the excess pressure in sw

No	Type of injury	Characteristic features	Δp_F, *bar*
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 excess pressure in SW*

No	*Type of destruction*	Δp_F *, bar*
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*

With account for the presented criteria, Fig. 3 shows the ranges of distances and energies of explosion causing the respective consequences.

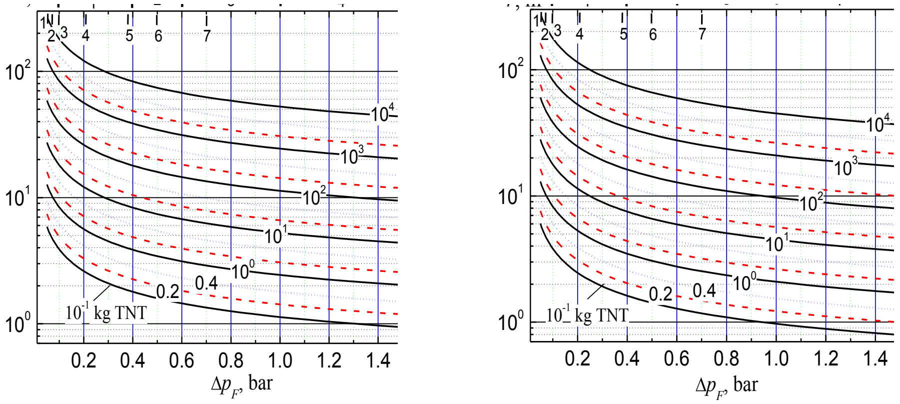

Figure 3. Dependence of the type of injuries and characters of destructions on the energy of explosion and the distance to its epicenter: left – condensed explosives; right – fuel-air mixtures. Ranges 1–4 refer to the typical human injuries (Table 1), figures 1–8 indicate the ranges of different zones of destruction under the effect of shock waves (Table 2) [5].

Conclusion

The results of multiple systematic calculations of the dynamics of explosion are presented. these results allowed thorough description of the spatial-temporal pattern of flow, the process of the transfer of energy of explosion products to the surrounding medium, formation, propagation, and decay of a shock wave. Relations of the geometric and energy similarity of explosion processes are considered. The obtained results are compared with the approximation of a strong point explosion, theoretical and experimental literature data. The effect of the shock wave on people and objects of the infrastructure are analyzed. Approximate dependences of the value of excess pressure behind the shock wave front – the main factor determining the effect of explosion on the surrounding medium – on the energy and distance to its epicenter are obtained.

The suggested models, software, and conducted computational experiments can form a basis for development of engineering techniques for estimation of the consequences of explosions of natural and man-caused character.

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