Journal of Engineering Physics and Thermophysics, Vol. 73, No. 1, 2000

INTERACTION OF SHOCK AND DETONATION WAVES IN GAS MEDIA WITH DISPERSED MATERIALS AND SOLID BARRIERS

E. V. Borisov, O. G. Martynov, V. N. Mironov, and E. F. Nogotov

UDC 662.215.4

This work presents the results of an experimental and theoretical investigation of the breakdown of a solid material by shock and detonation waves and the subsequent interaction of the indicated waves with the formed gas suspension cloud.

Actively developed now are technologies which use heat-transfer, impact, and propellant properties of shock and detonation waves, such as drying and thermal treatment of materials [1, 2], their grinding [3], application of strengthening coatings [4], etc. Many processes involving wave interaction with various materials and barriers take place in space-rocket technology.

Studying the mechanism of wave interaction with materials and revealing its features can foster the development of entirely new technologies and methods. Some features will turn out to be very useful from the utilitarian viewpoint, and others, which manifest themselves negatively, will be minimized. The current work is an experimental and theoretical investigation of wave interaction with materials and barriers.

Figure 1 presents a schematic of the experimental setup. The detonation tube had an inside diameter of 92 mm and was 9.5 m long. An electric spark plug was mounted at one end of the tube and a membrane at the other. The membrane was fabricated from several layers of 0.11 mm-thick aluminum foil. The structure of the detonation tube provided tightness after mounting of the membrane.

As a combustible gas, use was made of a technical propane-butane mixture with air in various proportions. Alternate admission of the fuel-mixture components to the tube was carried out after its evacuation.

Pressure disturbances were recorded with a number of piezoceramic transducers placed along the tube. Their electric signals were displayed on a pulse oscilloscope and were photographed.

A combustion wave from the spark plug gradually accelerated and became a shock or detonation wave depending on the composition of the combustible mixture. Amplitudes of the wave parameters were at their maximum near the membrane. The combustion products were exhausted to an expansion chamber and a silencer.

In the current work consideration was given to the destructive effect of the wave on the membrane material or objects positioned inside the tube. It was found (Fig. 2) that, at a shock-wave velocity of up to 700–720 m/sec, tensile stresses in the membrane breaks produced in it with the formation, at the center, of a cavity up to 15–20 mm in diameter. From 10 to 14 radial cracks spread from this cavity to the periphery and intersected concentric cracks. The length of the cracks was 2–3 times larger than the cavity diameter. When the membrane thickness decreased by half at the same shock-wave velocity, the character of damage was retained but the cavity was enlarged to 40–50 mm. Its enlargement resulted from the separation of membrane parts along the concentric cracks as a consequence of the tensile radial stresses.

At shock-wave velocities within the range of 800–820 m/sec, the cavity became nearly equal to the tube cross section, and the membrane was broken down completely with the formation of fragments, whose number corresponded to that of the radial and concentric cracks. The character of this damage was retained until the shock wave converted to a detonation wave. Under the effect of the shock wave, the tensile stresses

---

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute," National Academy of Sciences of Belarus, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 73, No. 1, pp. 180-188, January-February, 2000. Original article submitted April 14, 1999.

1062-0125/2000/7301-0181$25.00

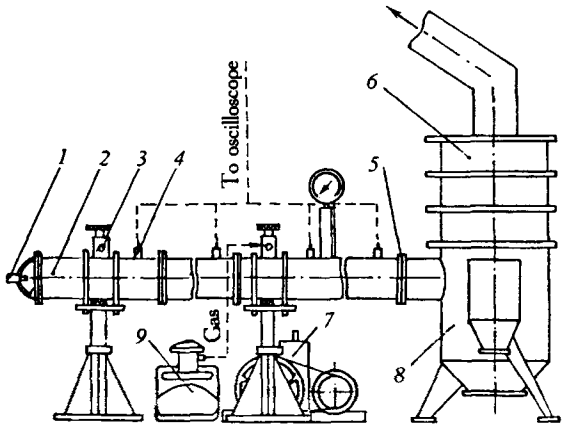

Fig. 1. Experimental setup: 1) spark plug; 2) detonation tube; 3) valve; 4) piezoelectric transducer; 5) membrane; 6) silencer; 7) vacuum pump; 8) expansion chamber; 9) gas cylinder.

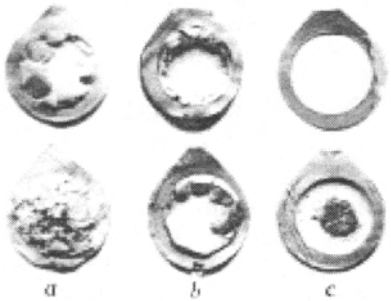

Fig. 2. Effect of shock and detonation waves on a metal membrane: in the upper horizontal row; the total thickness of several plates of aluminum foil was 220 μm; in the lower row, 440 μm. Wave velocity, m/sec: a) 700–720, b) 800–820; c) 1000–1700.

led to the formation of a network of radial and concentric cracks followed by the displacement and separation of diaphragm fragments at the most slack places. Thus, this process is viewed as breakdown of the material under the effect of the growth in an axisymmetric pressure field, continuously distributed in the medium, which is similar to a quasistatic load.

The membrane was broken down by a detonation wave (with velocities over 1000 m/sec) absolutely differently. By the action of the detonation wave, the membrane broke up into a great many fragments with the following composition: 20–25% up to 1 mm, 3–5% up to 5 mm, 60–65% up to 12 mm, and 3% over 12 mm. Moreover, the presence of 0.2–4.0 mm circular or oval openings in some fragments was noteworthy.

It could be assumed that a dynamic load of high intensity, which is characteristic of a detonation wave, causes impact damage to the membrane as a brittle body at the appropriate impact velocity. It turns out, however, that under the effect of the waves on viscoelastic materials, the damage pattern remains similar.

If a clay lump was placed in the tube, on interaction with a shock wave it was only crumpled and escaped from the tube to the expansion chamber in the form of a single piece or several fragments. When affected by a detonation wave, it was dispersed into submicron particles. The same pattern took place over a wide range of the clay humidities, from 2% (solid body) to 25% (viscoelastic mass), and also for clays of different compositions like red construction clay or bentonite.

The obtained damage pattern can in no way be related to classical wave characteristics like velocity, temperature, pressure, and density. Although high, they are not infinite and act for several milliseconds. Moreover, they are of the same order of magnitude for shock and detonation waves. For comparison it should be noted that, for a stoichiometric propane-butane mixture with air, before the origination of a self-sustaining

detonation wave the shock wave has a density of 5.4 kg/m^3, a velocity of 1008 m/sec, a temperature of 466 °C, and a pressure of $11.05 \cdot 10^5$ Pa, and the detonation wave, respectively, 2.4 kg/m^3, 1685 m/sec, 2095 °C, and $17.8 \cdot 10^5$ Pa. In this case, flow velocities of the gases themselves in these waves are the same, 760 m/sec. This suggests that yet another factor is operative in the detonation wave, apart from a certain excess of its parameters over the parameters of the shock wave.

It is possible to attempt to relate the obtained damage pattern [5] to the intricate structure of the front of the detonation wave. According to the concepts based on some studies [6-8], the narrow zone adjoining the shock front of the detonation wave is of intricate cellular structure. After the initial shock compression with the forefront, only a part of the mixture (about a half) is burnt. The remaining part is burnt later in the zone of interaction of transverse waves that make up the intricate cellular structure. The flow of supercompressed heterogeneities acts on the material similarly to the flow of hot solid particles.

If the effect of such quasiparticles, which bombard the material, exceeds its tensile strength, it begins to break down. The damage volume is proportional to the time of the effect. The main destructive factor is not so much the temperature of a gas quasiparticle as its kinetic energy. Quasiparticles time after time pull out (split off) microdoses of the treated material, causing its erosion and forming cavities (and in separate cases, also through channels), and the subsequent damage is completed by the total flow of combustion products that pulls apart the membrane or barrier at slack places in conformity with the already classical concepts of the resistance of materials.

Thus, the material becomes a set of particles, which subsequently interact with the wave by the known laws. This set of particles (we call it a gas suspension cloud) can afterward, in the zone of wave action, be subjected to one or another technological treatment, for example, dehydrated [9], calcined [10], accelerated to supersonic velocities [11], or ground [12], technically organizing a prevalent effect of one or another factor of the detonation wave (acceleration, temperature, velocity, or pressure).

At this stage it does not seem possible to construct a rigorous mathematical model of the interaction of a detonation wave with material. Let us assume that, when the material is broken to a finely divided state, the principal action on its integrity occurs in a region comparable in dimensions to the width of the chemical reaction zone, which is noticeably smaller than the characteristic dimensions of the wave (for example, in the compression phase). In view of this, as a first approximation we use the model of "instantaneous" damage to material with the formation of a gas suspension cloud as the front of the detonation wave passes.

The subsequent interaction of the detonation wave with the gas suspension cloud can be described mathematically within the framework of the classical model of a plane wave via differential equations which represent the laws of conservation of mass, momentum, and energy and are applicable to unsteady processes. With a dispersed component present in the gas medium, these equations are completed with analogous ones for a cloud of suspended dispersed particles with terms that characterize exchange reactions between the gas and the particles [13].

These equations are as follows:

for the law of conservation of mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0, \tag{1}$$

$$\frac{\partial \rho_{cl}}{\partial t} + \frac{\partial}{\partial x}(\rho_{cl} u_{cl}) = 0; \tag{2}$$

of momentum

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(\rho u^2 + P) = \rho_{cl} \frac{u_{cl} - u}{\tau_u} f, \tag{3}$$

$$\frac{\partial}{\partial t}(\rho_{cl} u_{cl}) + \frac{\partial}{\partial x}(\rho_{cl} u_{cl}^2) = -\rho_{cl} \frac{u_{cl} - u}{\tau_u} f; \tag{4}$$

and of energy

$$\frac{\partial}{\partial t}\left[\rho\left(c_V T+\frac{u^2}{2}\right)\right]+\frac{\partial}{\partial x}\left[\rho u\left(c_V T+\frac{P}{\rho}+\frac{u^2}{2}+Q_V\right)\right]=$$

$$=\rho_{cl}u_{cl}\frac{u_{cl}-u}{\tau_u}f+\rho_{cl}c_d\frac{T_{cl}-T}{\tau_T}g\,; \tag{5}$$

$$\frac{\partial}{\partial t}\left[\rho_{cl}\left(c_d T_{cl}+\frac{u_{cl}^2}{2}\right)\right]+\frac{\partial}{\partial x}\left[\rho_{cl}u_{cl}\left(c_d T_{cl}+\frac{u_{cl}^2}{2}\right)\right]=$$

$$=-\rho_{cl}u_{cl}\frac{u_{cl}-u}{\tau_u}f-\rho_{cl}c_d\frac{T_{cl}-T}{\tau_T}g\,. \tag{6}$$

The equation of state of the gas is

$$P=\frac{R^*}{\mu}\rho T\,. \tag{7}$$

Unlike the Stokes law, the particle resistance was defined by the expression

$$f=\left(1+\frac{\mathrm{Re}^{0.5}}{6}+\frac{\mathrm{Re}}{60}\right)[1+\exp(-0.427\mathrm{M}^{-4.63}-3\mathrm{Re}^{-0.88})]\,. \tag{8}$$

Heat transfer was assumed to obey the Ranz–Marshall law

$$g=1+0.3\,\mathrm{Pr}^{1/3}\,\mathrm{Re}^{1/2}\,. \tag{9}$$

The Reynolds criterion and the Mach number were defined by the expressions

$$\mathrm{Re}=\frac{\rho d_d\,(u-u_{cl})}{\eta}\,, \tag{10}$$

$$\mathrm{M}=\frac{u-u_{cl}}{c_s}=\left(\frac{\mu}{\gamma R^* T}\right)^{0.5}(u-u_{cl})\,. \tag{11}$$

The Prandtl number was taken to be constant, Pr = 0.75. The temperature dependence of the dynamic viscosity η and thermal conductivity of the gas η was determined by the Sutherland equation [14]

$$\frac{\lambda}{\lambda_0}=\frac{\eta}{\eta_0}=\left(\frac{T}{T_0}\right)^{3/2}\frac{T_0+T_S}{T+T_S}\,, \tag{12}$$

where the Sutherland constant for air is T_s = 114 K, and η_0 and λ_0 are taken at T_0 = 273 K. The relaxation times for momentum and energy were

$$\tau_u=\frac{1}{18}\frac{\rho_d d_d^2}{\eta}\,,\quad \tau_T=\frac{1}{12}\frac{\rho_d c_d d_d}{\lambda}\,. \tag{13}$$

According to the Zel'dovich–Dering–Neumann model, heat release in the detonation was assumed to occur in a narrow zone of finite length that adjoin the front. With account for the evaluation of the induction time and sizes of the flame cell, in conformity with the model of cellular structure of the detonation front the

length of the heat release zone was taken to be $\Delta x_Q = 0.04$ m. Mathematically this was expressed by introducing, in Eq. (5), a term that contained Q_V in the zone of 8 steps of the spatial grid that adjoins the front.

The above system of equations was solved numerically using the finite-difference method. Shocks were calculated, as in [15, 16], using a two-step version of the Lax–Wendroff scheme [17, 18]. Methodical calculations determined the optimum spatial step of the grid $\Delta x = 0.005$ m, which provides a solution error of 5–10%. A temporal step was chosen from the condition of preservation of the computation stability. Damping methods were used for suppressing oscillations of the numerical solution. Still, in some cases with pressure drops over $100 \cdot 10^5$ N/m^2, the solution was "noisy" due to the oscillations because of which, as in [16], some important, theoretically well-studied details of the wave profile and propagation were concealed. Therefore, subsequent calculations were carried out by the method of correction of flows [19], which, alongside the numerical diffusion that provides monotony of solution, used an antidiffusion stage that precludes nonphysical emissions. This permitted calculation of a very detailed pattern of the interaction of shock and detonation waves with a cloud of dispersed particles.

The results of the methodical calculations by this algorithm for pure air and its mixture with propane-butane [20] exactly coincided in magnitude and in all details of the profile of wave characteristics (temperature, density, and pressure) with the results calculated according to classical concepts that are presented, for example, in [21, 22].

For illustrating the capabilities of the computational method used in this work, below we present data on the interaction of shock and detonation waves with a gas suspension of aluminum powder. The gas medium was a stoichiometric propane-butane mixture with air: $\mu = 29.57$ kg/kmole, $Q_V = 2.77 \cdot 10^6$ J/kg, $\rho = 1.32$ kg/m^3 under normal conditions, $P_0 = 10^5$ N/m^2, $T_0 = 273$ K, $c_s = 324$ m/sec, $\gamma = 1.37$, and $c_V = 760$ J/(kg·K). The aluminum powder had the following characteristics: $d_d = 10^{-4}$ m, $c_d = 880$ J/(kg·K), $\rho_d = 2.7 \cdot 10^3$ kg/m^3, and $\rho_{clQ} = 2$ kg/m^3.

For modeling the effect of a shock or detonation wave incoming onto a cloud of pulverized particles, it is necessary to model the origination of the wave itself and then its propagation before meeting with the cloud. A stable pattern of the wave origination and propagation from rest was realized by specifying initial and boundary conditions, which correspond to an instantaneous break of the diaphragm at the initial instant between high- and low-pressure regions in the tube. Here, the following initial and boundary conditions were specified. The diaphragm was placed in the middle of the tube ($x = 0$). At the instant $t = 0$, to the right of the diaphragm ($x > 0$) the pressure was equal to atmospheric pressure ($P_0 = P_1 = 10^5$ N/m^2). The gas component was at rest ($u = 0$). The gas temperature to the left and to the right of the diaphragm was the same, $T_0 = 273$ K. In the left half of the tube, the gas was compressed to the pressure P_4 and was also at rest: $u = 0$ for $t = 0$ and $x < 0$. The left end of the tube at the distance $x = 6$ was shut so that $u = 0$ was set at the left boundary of the calculation domain for $t > 0$. The cloud of dispersed material that was at rest at the initial instant was located to the right of the diaphragm at a distance of 2 m.

After the diaphragm was broken, a rarefaction wave with the parameters T_3, T_3, u_3, and ρ_3 propagated to the left, and a shock wave with the parameters P_2, T_2, u_2, and ρ_2 propagated to the right and subsequently encountered the dust cloud.

The detonation wave was initiated by the preliminary generation of such a powerful shock wave that its parameters were sufficient for igniting the fuel mixture and exciting a self-sustaining reaction. The self-ignition temperature for a stoichiometric propane-butane mixture with air is 739 K. If the initial pressure of the fuel mixture is $P_4 = 767 \cdot 10^5$ Pa, then the shock wave, formed after the diaphragm break, according to calculations by the classical model [21, 22], has parameters ($T_2 = 739$ K and $P_2 = 11.05 \cdot 10^5$ Pa) sufficient for the self-ignition of this mixture and for the development of a detonation wave. Proceeding from the evaluation of the induction time and wave velocity it was assumed that the detonation wave originated from the shock wave at a distance of 1 m from the initial position of the diaphragm. At this distance, the heat source Q_V began to operate in the above-mentioned zone that adjoined the front. Within several spatial steps of the grid, the parameters of the calculated wave attained steady values, which fit the values for the detonation wave calculated by the classical model.

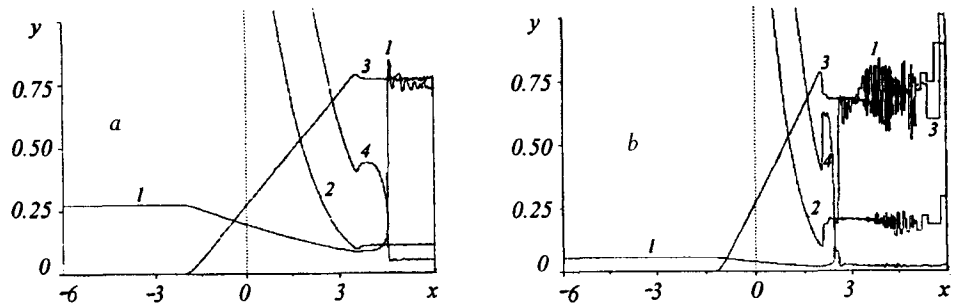

Fig. 3. Profiles of shock (a) and detonation (b) waves: 1) gas temperature, $T \cdot 10^{-3}$ K (a); $T/3000$ K (b); 2) pressure, $P \cdot 10^{-7}$ Pa; 3) velocity, $u \cdot 10^{-3}$ m/sec; 4) density, $\rho \cdot 10^{-2}$ kg/m^3.

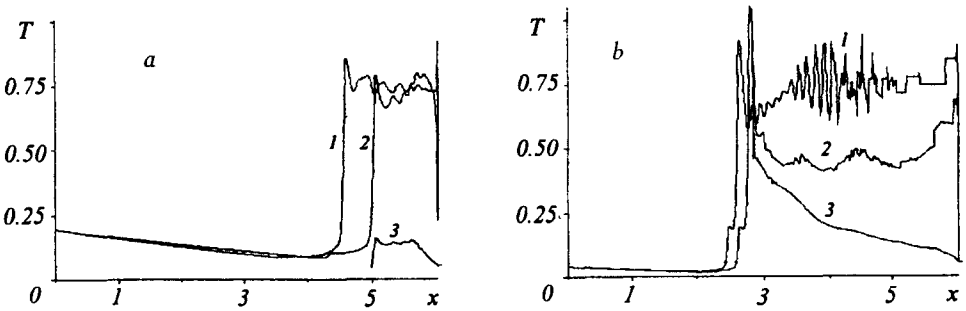

Fig. 4. Temperature profiles: a) in a shock wave, $T \cdot 10^{-3}$ K, and b) in a detonation wave, $T/3000$ K (1) gas temperature in the absence of particles; 2) in the presence of particles; 3) particle temperature).

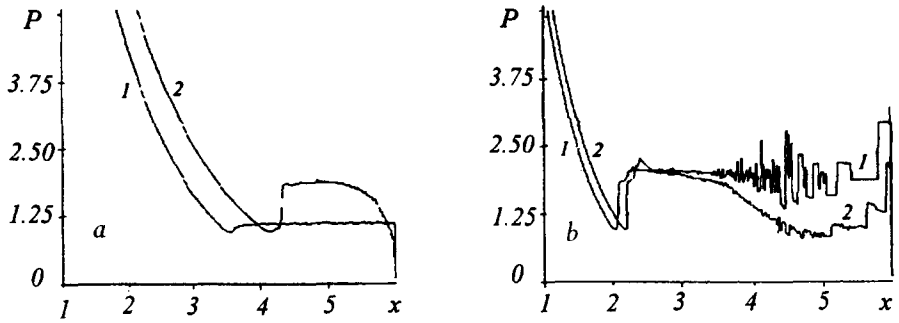

Fig. 5. Pressure profiles, $P \cdot 10^{-6}$ Pa, in shock (a) and detonation (b) waves: 1) gas pressure in the absence of particles; 2) in the presence of particles.

The wave thus formed within 1 m encountered the dust cloud. Figures 3-7 illustrate the calculated results. The profiles of wave characteristics are shown for an instant of the wave reaching a mark of 6 m from the diaphragm. The characteristics of the particles and the waves in pure gas and dust-laden gas in shock and detonation modes were compared.

A so-called "scraper" effect is seen clearly that lies in the total entrainment of particles by the passing wave, an increase in the density of the particle cloud ahead of the contact surface between hot and cold gases, and the absence of particles behind it (Fig. 7).

The presence, in the equation, of a term representing the heat release Q_V in the detonation wave causes, in comparison with a shock wave, a strong pulsation of the parameters in the forepart of the wave during its propagation in a pure gas, which outwardly resembles the actual pulsation of detonation waves. In the interaction with the dust cloud, the amplitude of these pulsations decreases sharply. Work [23] notes the fundamental instability of a steadily propagating shock wave relative to unsteady disturbances of one or another type. Arti-

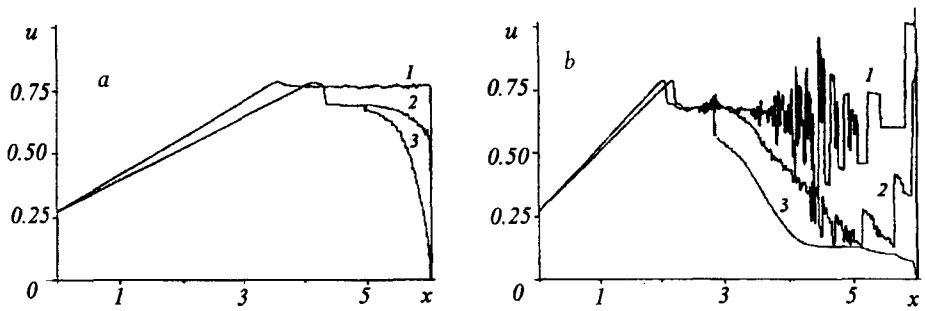

Fig. 6. Velocity profiles, $u \cdot 10^{-3}$ m/sec, in shock (a) and detonation (b) waves: 1) gas velocity in the absence of particles; 2) in the presence of particles; 3) particle velocity.

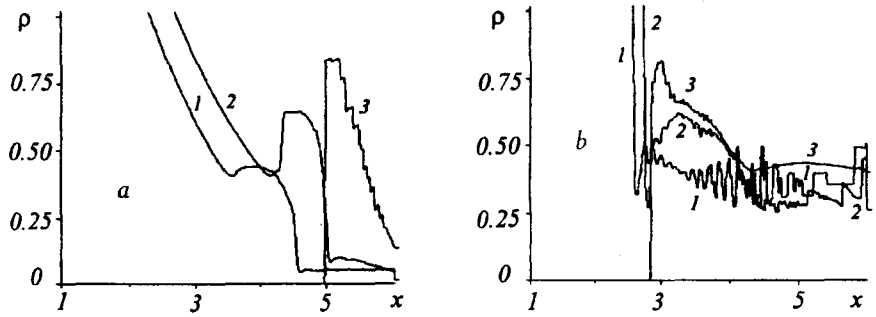

Fig. 7. Density profiles: a) in a shock wave, $\rho \cdot 10^{-2}$ kg/m^3 (1, 2), $\rho/15$ kg/m^3 (3), and b) in a detonation wave, $\rho/5$ kg/m^3 (1) gas density in the absence of particles; 2) in the presence of particles; 3) density of a particle cloud).

ficial smoothing of pulsations in the present work would lead to the loss of essential details and to a qualitative and quantitative distortion of the process.

In conclusion it should be noted that, although the construction and theoretical substantiation of a rigorous model of breakdown of solid materials by a detonation wave requires additional investigations, at this stage the following inferences can be drawn with a sufficient degree of certainty:

1) the mechanisms of breakdown of barriers by shock and detonation waves are significantly different,

2) the key role in the breakdown of barriers by a detonation wave is played by local elements of the cellular structure formed in a nonuniform energy release in the zone of chemical reaction of the detonation wave.

The mathematical model of wave interaction with gas suspensions based on classical concepts and the devised numerical methods for this problem give values of the wave parameters that fit the classical theory. The mathematical model permits its relatively simple adaptation to special features of processes via substituting or introducing, in the equations, new terms which account for these special features.

The possibility of describing in detail and studying the processes appreciably broadens the range of quantitative and qualitative concepts of wave interaction with barriers, which are needed for developing new technologies and designing new systems and facilities for space-rocket technology.

NOTATION

ρ, density, kg/m^3; t, time, sec; x, distance, m; u, velocity, m/sec; P, pressure, Pa; T, temperature, K; R^*, universal gas constant, J/(mole·K); γ, adiabatic exponent; μ, molecular weight, kg/kmole; c_s, sonic-wave velocity, m/sec; Q_V, specific energy of chemical transformation, J/kg; d_d, particle diameter, m; c_d and c_V, spe-

cific heat of particle material and gas at constant volume, J/(kg·K); f, coefficient of aerodynamic drag of particles; g, coefficient of rate of heat transfer between gas and particle; Re, Reynolds criterion; M, Mach number; Pr, Prandtl number; η, dynamic viscosity, (N·sec)/m^2; λ, thermal conductivity of gas, W/(m·K); T_S, Sutherland constant, K; τ_u and τ_T, relaxation times of momentum and energy, sec; Δx_Q, length of heat release zone, m. Subscripts: 0, initial value; cl, cloud; d, particle; s, sonic wave; S, Sutherland factor; u, velocity factor; T, temperature factor; V, volume (constant); Q, heat of chemical reaction; 1, zone of undisturbed gas; 2, zone of shock wave; 3, rarefaction zone; 4, high-pressure zone.

REFERENCES

1. D. M. Kukui, V. D. Bolotskii, E. V. Borisov, O. G. Martynov, and V. N. Mironov, in: *Abstr. 2nd Scientific-Technical Conf. "Resources-Saving and Environmentally Safe Technologies,"* Grodno, October 8-9, 1996 [in Russian], Grodno (1996), pp. 145-146.
2. E. V. Borisov, O. G. Martynov, and V. N. Mironov, in: *Collection of Papers "Heat and Mass Transfer–97"* [in Russian], Minsk (1997), pp. 69-74.
3. I. I. Piunovskii, E. V. Borisov, and O. G. Martynov, in: *Proc. Int. Scientific-Practical Conf. Dedicated to the 50th Anniversary of the Belarusian Scientific Research Institute of Agriculture Mechanization "Scientific and Technical Progress in Agricultural Production,"* Minsk, September 18-19, 1997 [in Russian], Minsk (1997), pp. 109-114.
4. A. I. Zverev and I. Yu. Miroshnichenko, *Poroshk. Metallurg.*, **119**, No. 11, 36-47 (1972).
5. E. V. Borisov, O. G. Martynov, and V. N. Mironov, in: *Proc. 3rd Minsk Int. Forum "Heat and Mass Transfer–MIF-96,"* Minsk, May 20-24, 1996 [in Russian], Vol. 3, Minsk (1996), pp. 115-119.
6. V. V. Mitrofanov and V. A. Subbotin, *Combustion and Explosion* [in Russian], Moscow (1997), p. 477.
7. V. A. Subbotin, *Fiz. Goreniya. Vzryva*, No. 3, 486-491 (1975).
8. A. A. Vasil'ev, Yu. A. Nikolaev, and V. Yu. Ul'yanitskii, *Fiz. Goreniya. Vzryva*, No. 3, 404-409 (1977).
9. E. V. Borisov, *Device for Thermal Treatment of Articles*, Inventor's Certificate No. 1185036, USSR: MKI^3 F 26 B 9/16, 3/34. Otkryt. Izobret., No. 28, 130 (1986).
10. E. V. Borisov, V. N. Yaglov, and O. S. Babushkin, *Method of Producing Powders of High-Melting Oxides*, Inventor's Certificate No. 1649738, USSR: MKI5 22 F 9/16, C 01 B 13/14. Published with the mark "Publication is Prohibited."
11. L. V. Al'tshuler, *Zh. Prikl. Mekh. Tekh. Fiz*, No. 4, 93-103 (1978).
12. B. E. Gel'fand, S. A. Gubin, S. M. Kogarko, and B. N. Palamarchuk, *Zh. Prikl. Mekh. Tekh. Fiz.*, No. 1, 61-66 (1975).
13. F. Marbl, *Mekhanika. Respubl. Mezhvedomstv. Sb.* (Moscow), **130**, No. 6, 25-27 (1971).
14. L. G. Loitsyanskii, *Mechanics of Liquids and Gases* [in Russian], Moscow (1970).
15. A. D. Gol'tsiker, S. V. Tarakanov, O. M. Todes, and S. A. Chivilikhin, *Zh. Prikl. Mekh. Tekh. Fiz.*, No. 2, 57-66 (1977).
16. O. M. Todes and S. V. Tarakanov, *Fiz. Aerodispersn. Sistem, Respubl. Mezhvedomst. Sb.* (Leningrad), Issue 16, 88-93 (1977).
17. P. D. Lax and B. Wendroff, *Comm. Pure Appl. Math.*, No. 3, 217-237 (1960).
18. P. D. Lax and B. Wendroff, *Comm. Pure Appl. Math.*, No. 17, 381-398 (1964).
19. E. S. Oran and J. P. Boris, *Numerical Simulation of Reactive Flow*, Elsevier Science Publ. (1987).
20. E. V. Borisov, O. G. Martynov, V. N. Mironov, and E. F. Nogotov, in: *Proc. 3rd Minsk Int. Forum "Heat and Mass Transfer–MIF-96,"* Minsk, May 20-24, 1996 [in Russian], Vol. 9, Pt. II, Minsk (1996), pp. 200-206.
21. G. V. Lipman and A. Roshko, *Elements of Gas Dynamics* [in Russian], Moscow (1960).
22. A. S. Sokolik, *Self-Ignition, Flame, and Detonation in Gases* [in Russian], Moscow (1960).
23. S. K. Aslanov, *Fiz. Aerodispersn. Sistem, Respubl. Mezhvedomst. Sb.* (Kiev), Issue 34, 79-90 (1991).