ATTENUATION OF AIR SHOCK WAVES BY LAYERS OF DUSTY GAS AND LATTICES

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The problem of air shock wave attenuation is of great practical significance in many areas of modern technology, from the mineral extraction industry [1] to thermonuclear energy generation, where attempts are being made to shield impulsive thermonuclear reactors from the action of thermonuclear microexplosions [2]. One technical solution to this problem is the use of protective screens of dust (or droplet) layers or lattices.

The currently available engineering methods for calculating efficiency of such protective screens rely on elementary classical gas dynamics theory of shock waves without use of modern techniques from the field of mechanics of multiphase media. In such a situation the only practical method of study is large-scale field or laboratory experiment. For these reasons screening devices presently used do not provide effective control or optimization with regard to shock wave, screen system parameters, etc. Successful optimization of shield screens can be accomplished by use of adequate models of heterogeneous methods and numerical techniques.

The present study will consider the possibility of using the concept of a frozen gas suspension to describe the laws of attenuation and interaction of shock waves in layers of dusty gas and lattices. The study will be carried out for brief shock waves, in which the duration of the compression phase τ_+ is much less than the characteristic relaxation times for velocity τ_u and temperature τ_T of the phases ($\tau_+ \ll \tau_u, \tau_T$). With this condition, motion of dispersed particles in the gas behind the shock wave is not considered. The region of the gas with lattices is modeled as a two-temperature gas mixture with immobile particles of condensed material. The lattice points are considered particles of the frozen suspension. The effect of lattice connections on the gas is neglected (it is assumed that the thickness of the connections is much less than the size of the lattice points). The high efficiency in attenuating air shock waves of screening layers of gas suspensions and lattices for very small volume concentrations of the condensed phase (~0.1-1%) will be shown. Individual aspects of the question of applicability of the frozen gas suspension model for description of propagation of a finite duration shock wave were considered in [3-7].

1. Formulation of the Problem and Basic Equations. We will study the passage of a planar shock wave with falling pressure profile through a layer of a movable or arbitrarily fixed suspension of solid particles located ahead of a rigid wall. Our goal is to study the effect of such screening layers on shock wave attenuation and the mechanical action of the wave on the wall as functions of the concentration and size of the particles in the dispersed condensed phase.

We describe the process of shock wave propagation in gas suspensions and lattices within the framework of conventional concepts of the mechanics of multiphase media [8]. The corresponding system of differential equations [8, 9] which describes planar one-dimensional nonsteady-state motion of a two-velocity, two-temperature mixture of an ideal calorically perfect gas and monodispersed incompressible particles in dimensionless form appears as follows:

$$\frac{\partial\rho_i}{\partial t}+\frac{\partial\rho_i u_i}{\partial x}=0 \quad (i=1,2), \tag{1.1}$$

$$\frac{\partial\rho_i u_i}{\partial t}+\frac{\partial\rho_i u_i^2}{\partial x}+\frac{[2-i+(-1)^i\beta]}{\gamma}\frac{\partial p}{\partial x}=(-1)^i(1-\beta')F, \quad \frac{\partial\rho_2 e_2}{\partial t}+\frac{\partial\rho_2 e_2 u_2}{\partial x}=Q,$$

$$\sum_{i=1}^{2}\left(\frac{\partial\rho_i E_i}{\partial t}+\frac{\partial\rho_i u_i E_i}{\partial x}+\frac{1}{\gamma}\frac{\partial p\alpha_i u_i}{\partial x}\right)=0,$$

$$\rho_i=\alpha_i\rho_i^0 \quad (\alpha_1+\alpha_2=1), \quad \beta=1.5\alpha_2, \quad \beta'=\beta+0.5\rho_1^0/\rho_2^0,$$

$$F=\rho_2(u_1-u_2)\left\{T_1^\varepsilon+\frac{\sqrt{\mathrm{Re}_0}}{6}[\rho_1^0(u_1-u_2)]^{0.5}T_1^{0.5\varepsilon}+\right.$$

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$$+\frac{\mathrm{Re}_0}{60}\rho_1^0(u_1-u_2)\Big\}\left[1+\exp\left(-0.427/\mathrm{M}_{12}^{4.63}\right)\right]\frac{1}{(1-\alpha_2)^{\varkappa}},$$

$$Q=\frac{\gamma}{\mathrm{Pr}_0}\rho_2\left(e_1-\frac{e_2}{\delta_0}\right)\Big\{\frac{2}{3}\exp(-\mathrm{M}_{12})T_1^{\theta}+$$

$$+0{,}153\,\mathrm{Re}_0^{0,55}\,\mathrm{Pr}_0^{0,33}\left(\rho_1^0|u_1-u_2|\right)^{0,55}T_1^{(0,67\theta-0,22\varepsilon)}\Big\},$$

$$p=\gamma(\gamma-1)\rho_1^0e_1,\quad T_1=\frac{p}{\rho_1^0},\quad e_i=E_i-\frac{u_i^2}{2},\quad a_1=\sqrt{\frac{p}{\rho_1^0}},$$

$$\mathrm{M}_{12}=\frac{|u_1-u_2|}{a_1},\quad \mathrm{Re}_0=\frac{\rho_{10}^0a_{10}d}{\mu_{10}},\quad \mathrm{Pr}_0=\frac{\gamma c_1\mu_{10}}{\lambda_{10}},\quad \delta_0=\frac{c_2}{c_1}.$$

Here the subscripts 1, 2 refer to gas and particle parameters; ρ_i, ρ_i^0, α_i, u_i, e_i, E_i are the mean and true densities, volume content, velocity, specific internal and total energy of the i-th phase; p and T are the pressure and temperature; F and Q are the interphase friction force and the intensity of contact heat exchange; β and β' are parameters considering the contributions of non-steady-state Archimedean forces and combined mass to the total interphase interaction force [10]; M_{12} is the Mach number relative to the gas motion; c_1, μ_{10}, λ_{10} are the specific heat, dynamic viscosity, and thermal conductivity of the gas in the unperturbed region; d is the particle diameter.

System (1.1) is characterized by the independent dimensionless parameters [11]

$$\gamma,\ \mathrm{Re}_0,\ \varepsilon,\ \theta,\ \delta,\ \mathrm{Pr}_0,\ \varkappa, \tag{1.2}$$

where Re_0 and Pr_0 are Reynolds and Prandtl numbers; δ is the ratio of the phase heat capacities; γ is the adiabatic index of the gas; ε and θ are the exponents in the temperature dependences of gas viscosity and thermal conductivity; $\varkappa$ is a parameter which considers particle crowding [8].

The initial conditions for the problem formulated above will be specified as in [10]: gas parameters on the shock wave pulse front ($x = x_*$) are related to gas parameters ahead of the shock wave by Rankin–Hugoniot relationships; gas parameters behind the front in the rarefaction zone ($0 \le x < x_*$) at the initial moment t = 0 are specified on the basis of isentropic relationships for a simple Riemann wave with rectangular gas velocity profile; in the unperturbed gas zone ($x_* < x < x_{**}$) and unperturbed suspension ($x_{**} \le x \le x_{***}$), the phase parameter distributions are assumed homogeneous:

$$\rho_1^0(x,0)=1,\quad \alpha_1(x,0)=1,\quad u_1(x,0)=0,\quad p(x,0)=1\qquad (x_*<x<x_{**}),$$
$$\rho_1^0(x,0)=1,\quad \alpha_1(x,0)=\alpha_{10},\quad \alpha_2(x,0)=\alpha_{20},\quad p(x,0)=1,$$
$$u_1(x,0)=u_2(x,0)=0\qquad (x_{**}\leqslant x\leqslant x_{***}).$$

For the boundary condition at the left (open) boundary x = 0, we take the condition of free passage of the gas phase, while at the right (closed) boundary $x = x_{***}$, we have equality to zero of the gas velocity $u_1(x_{***}, t) = 0$ and the condition of free passage for the particles [12].

From the initial conditions, in addition to Eq. (1.2) six more dimensionless parameters follow:

$$\mathrm{M}_0,\ X_*,\ X_{**},\ X_{***},\ m,\ \alpha_{20}$$
$$(X_*=|x_*|/L_u,\ X_{**}=|x_{**}-x_*|/L_u,\ X_{***}=|x_{***}-x_{**}|/L_u), \tag{1.3}$$

which characterize the intensity (M_0 is the Mach number) and extent X_* of the shock wave, the lengths of the unperturbed gas region X_{**} and screening layer X_{***}, referred to the characteristic Stokes length of the phase velocity equalization zone ($L_u = \tau_u a_{10}$); $m = \rho_{20}/\rho_{10} = \alpha_{20}\rho_2^0/\alpha_{10}\rho_{10}^0$ is the relative mass content of the suspension.

Thus, in the general case the solution of the problem depends on 13 dimensionless parameters, the major ones of which are γ, M_0, Re_0, m, X^*, X^{**}, X_{***}, given the conditions that the effects of phase temperature nonuniformity are small compared to the effects of phase velocity nonuniformity [11].

2. Schematization of the Frozen Flow. To describe the propagation of brief shock waves in gas suspension layers and lattices, it will also be desirable to employ a schematization of the frozen flow, according to which the suspension particles "do not participate" in

TABLE 1

d, μm	α_{20}, %	G_1	G_2	G_3	G_4	h/d
60	0,052			$5\cdot10^{-2}$	$8{,}4\cdot10^{-3}$	10
	0,1	$1{,}6\cdot10^{-2}$	$3{,}2\cdot10^{-2}$	$9{,}7\cdot10^{-2}$	$1{,}6\cdot10^{-2}$	8
	0,24			$2{,}3\cdot10^{-1}$	$3{,}9\cdot10^{-2}$	6
150	0,052			$7{,}9\cdot10^{-3}$	$1{,}3\cdot10^{-3}$	10
	0,1	$2{,}5\cdot10^{-3}$	$5{,}1\cdot10^{-3}$	$1{,}5\cdot10^{-2}$	$2{,}5\cdot10^{-3}$	8
	0,24			$3{,}6\cdot10^{-2}$	$6\cdot10^{-3}$	6
600	0,052			$5\cdot10^{-4}$	$8{,}4\cdot10^{-5}$	10
	0,1	$1{,}6\cdot10^{-4}$	$3{,}2\cdot10^{-4}$	$9{,}7\cdot10^{-4}$	$1{,}6\cdot10^{-4}$	8
	0,24			$2{,}3\cdot10^{-3}$	$3{,}9\cdot10^{-4}$	6

the motion, i.e., $u_2(x, t) \equiv 0$, $\alpha_2(x, t) = \alpha_{20}$. System (1.1) then reduces to the equations of gas dynamics, written with consideration of an "external" volume force F and a heat increment Q produced on the gas by the suspension of immobile particles (the heat increment equation for the dispersed phase is retained, only its convective term is dropped).

The use of the frozen gas suspension model for study of brief shock waves in mixtures with coarse heavy particles does not contradict any physical concepts. It is natural to expect that for short-term dynamic action of the gas on heavy and coarse particles, the latter may not be entrained into motion. For weak shock waves in gaseous suspensions, [3] proposed the four following asymptotic conditions which allow the possibility of schematizing the "frozen state" of the particles:

$$G_1 = \frac{L_+}{L_u} = \frac{18\eta_0}{\mathrm{Re}_*\mathrm{St}_*} \ll 1, \quad G_2 = \frac{L_+}{L_T} = \frac{12\eta_0\gamma}{\mathrm{Pr}_0\delta_0\mathrm{Re}_*\mathrm{St}_*} \ll 1,$$
$$G_3 = \frac{2L_+\alpha_{20}}{3L_u\mathrm{Pr}_0\eta_0} = \frac{12\alpha_{20}}{\mathrm{Pr}_0\mathrm{Re}_*\mathrm{St}_*} \ll 1,$$
$$G_4 = \frac{\alpha_{20}}{6\eta_0}\left|\frac{\gamma-1}{\mathrm{Pr}_0} - \frac{3}{2}\right|\frac{L_+}{L_u} = \frac{3\alpha_{20}\left|\frac{\gamma-1}{\mathrm{Pr}_0} - \frac{3}{2}\right|}{\mathrm{Re}_*\mathrm{St}_*} \ll 1 \quad \left(\eta_0 = \frac{\rho_{10}^0}{\rho_2^0}\right). \tag{2.1}$$

Here L_+, L_u, L_T, Re_*, St_* are characteristic lengths of the shock wave, phase velocity, and temperature equalization zones, and the Reynolds and Strouhal numbers. The physical meaning of the first two criteria of Eq. (2.1) was explained above, while the third and fourth express the condition of a small but finite change in particle entropy behind short shock waves and the absence of an effect on the gas of waves incident upon and reflected from particles within the gas. The criteria of Eq. (2.1) will be used below to analyze the process of propagation of a shock wave of moderate intensity in gas suspensions.

The concentrated suspension of "frozen," i.e., "fixed to the ether," immobile, solid particles can be considered [5-7] as the simplest possible model lattice, in which the particles serve as lattice points connected by the finest-possible weightless, undeformable filaments. Such a lattice can be treated as a perforated bulkhead [1, 13] for which the analog of the perforation coefficient is the volume (surface [14]) content of gas in the lattice, α_{10}. For an ordered cubic lattice, the ratio of the distance between the "frozen" particles h and their diameter d can be expressed in terms of the volume concentration of the suspension α_{20} with the relationship [14]

$$h/d = (\pi/6\alpha_{20})^{1/3}. \tag{2.2}$$

3. Results of the Numerical Study. Numerical integration of system (1.1) with the initial and boundary conditions introduced above can be accomplished by the coarse particle method [12] using the algorithm of [15]. The accuracy of the calculations was controlled by performing repeated calculations with decreasing steps in time and space. All calculations were performed for a mixture of air with iron particles using the following values of thermodynamic parameters: T_0 = 293 K, ρ_{10}^0 = 1.21 kg/m³, γ = 1.4, a_{10} = 341 m/sec, c_1 = 716 m²/(sec²·deg), $\mu_{10} = 1.85\cdot10^{-5}$ kg/(m·sec), λ_{10} = 0.026 kg·m/(sec³·deg), Pr_0 = 0.71, $\varepsilon = \theta = 1$, $\varkappa = 3$, ρ_2^0 = 7800 kg/m³, c_2 = 460 m²/(sec²·deg), δ_0 = 0.64, $\eta_0 = 1.55\cdot10^{-4}$, with shock wave parameters M_0 = 4.2, x_* = 0.45 m, geometric parameters $|x_{****} - x_{***}|$ = 1.5 m, $|x_{***} - x_{**}|$ = 0.05 m.

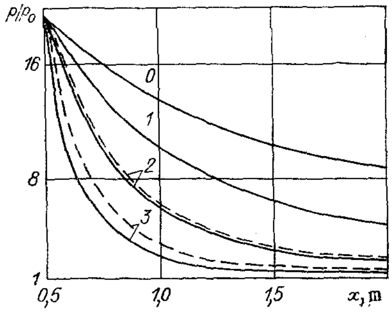

Fig. 1

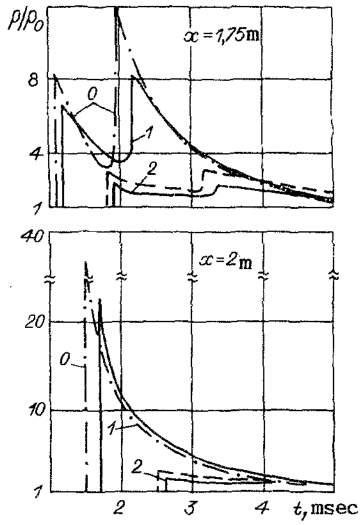

Fig. 2

The numerical experiments were performed for a wide range of volume content of the dispersed phase and particle size: $0 \le \alpha_{20} \le 6.5\%$ and $60 \le d \le 1200$ μm.

For these conditions Table 1 shows numerical values of the dimensionless parameters G_i ($i = 1$-4), Eq. (2.1), and h/d, Eq. (2.2), corresponding to various values of d and α_{20}. It is evident from Table 1 that satisfactory description of the rules of shock wave damping in gas suspensions can be expected within the framework of the frozen schematization, for example, at $\alpha_{20} = 0.1\%$ and $d \geqslant 60$ μm or at $\alpha_{20} = 0.24\%$ and $d \geqslant 150$ μm. To establish reliability of the consequences following from the asymptotic estimates of Eq. (2.1), we turn to the the results of the numerical study.

As an example, Fig. 1 shows the law of pressure amplitude falloff behind a brief shock wave in a dusty gas at $\alpha_{20} = 0.1\%$ ($m = 6.5$) as a function of distance traversed. Curves 1-3 correspond to suspensions of particles with diameters d = 600, 150, and 60 μm, while 0 is a solution for a gas without particles ($\alpha_{20} = 0$). The solid lines are solutions obtained within the framework of the frozen gas suspension scheme, while the dashes are solutions for a two-velocity, two-temperature model of the dispersed gas-particle mixture. It is evident from Fig. 1 that the solutions obtained within the framework of the precise two-velocity and the approximate one-velocity (frozen) schematization of the gas suspension differ only insignificantly. The difference decreases with increase in size of the dispersed particles (compare curves 1-3).

Figure 2 shows typical calculated "oscillograms" of pressure behind the incident shock wave and the wave reflected from the wall in the gas suspension. The upper "oscillogram" corresponds to a coordinate 0.25 m removed from the wall, while the lower is for the coordinate of the boundary wall. Curves 1, 2 are for suspensions with particle diameters d = 600 and 60 μm. All remaining notation and mixture parameters are as in Fig. 1. It is evident from Fig. 2 that the frozen solution describes the change in pressure with time behind the shock wave in a gas suspension well, even for fine particles with $d \cong 60$ μm. The frozen solution for coarse particles with $d \cong 600$ μm is not shown in Fig. 2 because it differs so insignificantly from that obtained with the general model of a two-velocity gas-particle continuum.

Figure 3 shows the change in air shock wave pressure as a function of the distance traversed by the wave in a layer of dusty gas with a high concentration of dispersed particles $\alpha_{20} = 0.24\%$ ($m = 15.6$). All notation and particle parameters are as in Fig. 1. The good agreement of solutions obtained in both the two-velocity and one-velocity (frozen) gas suspension flow schematizations for particle diameters $d \geqslant 150$ μm is evident. In particular, for $d = 600$ μm the approximate frozen solution practically coincides with the precise one.

The effect of the defining parameters of the lattice screening layers (volume content of the condensed phase and size of the lattice points) on the degree of shock wave attenuation is demonstrated in Fig. 4 by curves showing the change in dimensionless peak pressure ($\Lambda_p = p_{max}/p^0_{max}$) and the excess gas pressure impulse ($\Lambda_I = I_{p,max}/I^0_{p,max}$) on the barrier wall as a function of α_{20} and d (lines 1-3 correspond to d = 600, 150, 60 μm). Here, as in [10], for the excess gas pressure impulse, we use an integral of the form

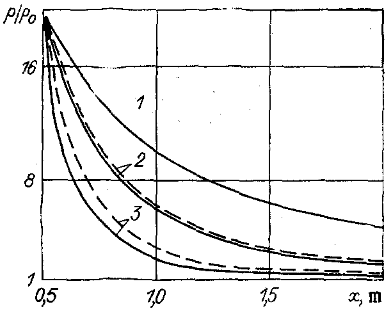

Fig. 3

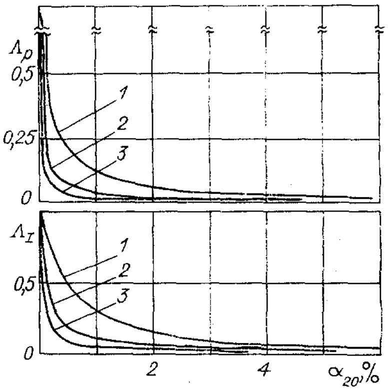

Fig. 4

$$I_p(x_{***}, t) = \int_{t_*}^{t} [p(x_{***}, \tau) - p_0]\, d\tau,$$

where $p(x_{***}, \tau)$, p_0 are the current and initial unperturbed gas pressure on the barrier wall; t_* is the characteristic time of commencement of perturbation of the medium by the shock wave; p^0_{max}, $I^0_{p,max}$ are the values of p and Ip in the absence of the lattice ($\alpha_{20} = 0$). In the example presented $p^0_{max} = 3.8$ MPa, $I^0_{p,max} = 2000$ kg/(m·sec).

It is evident from Fig. 4 that the peak values of pressure and excess gas pressure impulse on the barrier wall decrease exponentially with the volume content of the condensed phase of the lattice α_{20}, i.e., $\Lambda_p \sim \exp(-\varphi\alpha_{20})$ and $\Lambda_I \sim \exp(-\psi\alpha_{20})$. The attenuation coefficients φ and ψ then depend on d, their values being higher for smaller d. It follows from this that the greatest attenuation of air shock waves by screening layers of dusty gas and lattices is achieved at high α_{20} and low d (high φ and ψ). Identical reductions in maximum shock wave pressure and impulse (Λ_p = const, Λ_I = const) can be realized by variation of the parameters α_{20} and d. For example a ten-fold reduction in maximum pressure ($\Lambda_p = 0.1$) on the barrier wall can be achieved at $0.1 \le \alpha_{20} \le 1.5\%$ and $60 \le d \le 600$ μm. The same reduction in excess pressure impulse occurs at $0.25 \le \alpha_{20} \le 2.8\%$ and $60 \le d \le 600$ μm.

In addition to the excess gas pressure impulse on the wall, the present study calculated the impulsive action of the particles on the wall $I_u(x_{***}, t) = \frac{1}{2}\int_{t_*}^{t} \rho_2(x_{***}, \tau)[u_2(x_{***}, \tau)]^2\, d\tau$. The calculations showed that within the phase and shock wave parameter range considered when the gas suspension layer is located directly at the wall, the particle impulse behind a triangular shock wave is small compared to the excess gas pressure impulse ($I_{u,max}/I_{p,max} \leqslant 0.04$). This fact was discussed in [10, 16]. It should be noted that the value of particle impulse on the wall can be relatively large when the gas suspension layer is located a distance from the wall of the order of magnitude of the characteristic length of the gas-particle velocity equalization zone $\Delta x \geqslant L_u$ [16, 17].

Thus the numerical study performed has established that to evaluate the efficiency of attenuation of short shock waves by screening layers of dusty gas, the significantly simpler frozen solutions which assume absence of motion of the particles of the dispersed condensed phase are completely satisfactory. The asymptotic solutions obtained in [3], which permit the frozen gas suspension flow schematization behind brief shock waves, can be used to analyze propagation of a shock wave of finite duration and moderate intensity in dusty gases. The presence of screening layers of fine cell lattices with even a very small volume content of solid material ($\alpha_{20} \sim 0.1$-1%) leads to intense attenuation of air shock waves.

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