an increase in reflection pressure, as was confirmed in experiment. The above indicates the validity of the proposed physical analysis of the results obtained, and indicates the necessity of considering the effects of length of the wave perturbation and pressure profile in the relaxation zone zone on reflected wave parameters in two-phase media.

For a deeper understanding of the observed phenomena it will be necessary to analyze the effect of relaxation processes on formation and reflection of shock waves in foam.

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INFLUENCE OF SCREENING GAS-SUSPENSION LAYERS ON SHOCK-WAVE REFLECTION

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UDC 532.529:518.5

More and more attention has recently been spent on investigating the urgent problem of nonstationary wave flows of gas-suspensions. The main results obtained are reflected in a number of papers [1-4] and are examined in sufficient detail [5]. An analysis of weak shock propagation in gas suspensions is represented in [6] on the basis of the Burgers equation, while strong shocks in a gas with disperse particles are investigated in [7, 8]. Analysis of the literature shows that stationary shock-wave propagation and interaction with obstacles in gas-suspensions have been studied well enough. At the same time there are practically no papers devoted to the investigation of the nonstationary process of finite-duration shocks interacting with obstacles [5].

Results of a numerical investigation of the influence of the screening gas-suspension layer on the reflection of a plane nonstationary shock from a rigid wall are represented in this paper. The results can be useful in the design of systems of dust protection from the action of shocks and the analysis of possibilities of gasdynamics methods of depositing powder coatings [9].

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1. Formulation of the Problem

On a homogeneous gas-suspension layer of width l_s that screens a rigid, fixed wall, let a plane finite-duration shock be incident. We will study the influence of the layer on the effect of the wave on the obstacle. We will consider the motion of the gas mixture with the solid disperse particles under the fundamental assumptions in [1-4]. We assume that the distance within which the mean flow parameters vary is significantly greater than the particle dimensions and their separation (outside the shock surfaces in the carrying phase); the particles are spherical and the mixture is monodisperse; viscosity and heat-conduction effects are substantial only in interphase interaction processes; there are no particle fragmentation and collisions; no phase transformations occur. We use the model of a two-velocity and two-temperature continuum [1] to describe the unsteady flow of gas-suspensions. We consider the carrying continuum an ideal calorically perfect gas while the substance of the disperse phase is incompressible. We perform the computations of numerically integrating the closed system of differential equations of plane one-dimensional gas-suspension motion [10] by the method of coarse particle [4, 11, 12] with the extraction of different contact boundaries by using algorithms of localization type [13].

Let us note that the interphasal interaction force f is a set of several forces of different nature in the general case (the viscous friction force f_μ, Archimedes force f_A, apparent mass f_m, and Bass force f_B [14]):

$$f = f_\mu + f_A + f_m + f_B.$$

However, the contribution of the hereditary Bass force f_B to f for high Reynolds numbers relative to the particle flow is less significant than the contribution of f_A and f_m (whose contribution is, in turn, ordinarily significantly less than the contribution of f_μ). It is interesting to make appropriate estimates. The known integral expression for f_B has a rigorous foundation for $Re_{12} \ll 1$; however, taking into account that the role of the hereditary effect diminishes as Re_{12} increases, for $Re_{12} \gg 1$ it can be used as an upper bound for f_B. It can be shown that for large $Re_{12} \gtrsim 10^4$, when the Newton particle flow regime is realized with drag coefficient $C_d^0 = 0.44$, the ratio of f_B to f_μ is characterized by the dimensionless parameter K_N:

$$K_N = \sqrt{\frac{\mu_1}{\rho_{1*}^0 \tau_* u_*^2}} = \sqrt{\frac{\mathrm{Sh}}{\mathrm{Re}_*}},\quad \mathrm{Sh} = \frac{d}{u_* \tau_*},\quad \mathrm{Re}_* = \frac{d\rho_{1*}^0 u_*}{\mu_1},$$

where ρ_{1*}^0, u_*, τ_* are the characteristic values of the gas density, the relative phase velocity and the time of its change, and d is the particle diameter. Analysis of the dependence of the ratio f_B/f on the Strouhal number Sh shows that for $Re_{12} \gtrsim 10^4$ the maximum is $f_B/f < 0.06$. Therefore, the estimate of f_B known to be exaggerated even in the maximum indicates the small contribution of f_B to f for high $Re_{12} \gtrsim 10^4$. It should be emphasized that the upper bound of f_B is given; moreover, the ratio of the phase densities ρ_1^0/ρ_2^0 in shocks is not very small as a rule, hence, the contribution of f_m and f_A to f is ordinarily a more significant quantity than the contribution of f_B. The circumstances mentioned permit neglecting the hereditary force f_B, which radically simplifies execution of the numerical computations.

Initial Conditions. The gas parameters behind a shock (denoted by the subscript b) are related to the gas parameters ahead of the shock (denoted by the subscript 0) by the Hugoniot relationships

$$\frac{u_{1b}}{a_{10}} = \frac{2}{\gamma+1}\left(M_b - \frac{1}{M_b}\right),\quad \frac{p_b}{p_0} = 1 + \frac{2\gamma}{\gamma+1}(M_b^2 - 1),\quad \frac{\rho_{1b}^0}{\rho_{10}^0} = \frac{(\gamma+1)M_b^2}{2+(\gamma-1)M_b^2},$$

where p is the pressure, u is the velocity, M is the Mach number, and a_1, γ are the speed of sound and the adiabatic index of the gas. Here and henceforth, the subscripts 1 and 2 are used to denote the gas and particle parameters.

The gas parameter distribution behind the shock at the initial time t = 0 is given by assuming the velocity profile behind the shock rectilinear, and the state of the medium isentropic [10]:

$$u_1/u_{1b} = x/x_b,\ \rho_1^0/\rho_{1b}^0 = [\sigma(x)]^\delta,\ p/p_b = [\rho_1^0/\rho_{1b}^0]^\gamma,\ \alpha_1 = 1$$
$$(0 \leqslant x \leqslant x_b),\ \delta = 2/(\gamma-1),\ \sigma(x) = 1 - u_{1b}(1 - x/x_b)/a_{1b}\delta,$$
$$u_1 = 0,\ \rho_1/\rho_{10}^0 = 1,\ \alpha_1 = 1,\ p/p_0 = 1\ (x_b < x < x_s),$$
$$u_1 = 0,\ \rho_1/\rho_{10}^0 = \alpha_{10},\ \alpha_1 = \alpha_{10},\ p/p_0 = 1\ (x_s \leqslant x \leqslant x_w).$$

Here and henceforth, ρ_i, α_i are the mean density and volume content of the i-th phase (i = 1, 2), and x is the space coordinate. The subscripts b, s, and w denote the beginning coordinates of the shock, and the limits of the disperse screening layer and the obstacle.

The particle parameter distribution in the layer at t = 0 (including their temperature T_2) will be assumed homogeneous:

$$u_2 = 0,\ \rho_2/\rho_{20} = 1,\ \alpha_2 = \alpha_{20},\ T_2/T_0 = 1\ (x_s \leqslant x \leqslant x_w).$$

Boundary Conditions. Numerical computations were performed on a difference mesh covering a limited segment $[0, x_w]$ of the x axis. Its left boundary x = 0 is always assumed open and the condition of free phase penetration is posed there [4]

$$u_i(0_+, t) = u_i(0_-, t)\ (i = 1, 2).$$

For $x = x_w$ (the rigid wall), conditions of zero velocity for the gas and of free penetration for the particles [4] were given (the latter was modeled by "particle emergence from the game" during their inelastic interaction with the wall):

$$u_1(x_w, t) = 0,\ u_2(x_{w+}, t) = u_2(x_{w-}, t).$$

The possibility of substituting such a boundary condition for the particles in the problem under consideration follows from estimates and test computations that indicate the smallness of the momentum of the particles incident on the wall. This latter is associated with the fact that the particles in direct proximity to the wall are not accelerated successfully since the process of their entrainment into the motion in rapidly interrupted by the reflected shock. Particles more remote from the wall and which are successfully accelerated in the incident wave also do not carry their momentum to the wall since they succeed in being retarded by the gas behind the reflected wave.

2. Certain Results

Computations were performed for air mixtures with quartz sand particles with the following values of the heat conduction λ, the specific heat c, the viscosity μ, and the other phase thermodynamic parameters: T_0 = 293°K, p_0 = 0.1 MPa, c_p = 1005 $m^2/(sec^2 \cdot deg)$, γ = 1.4, a_{10} = 341 m/sec, ρ_{10}^0 = 1.21 kg/m^3, λ_1 = 0.026 $(kg \cdot m)/(sec^3 \cdot deg)$, $\mu_1 = 1.85 \cdot 10^{-5}$ kg/(m·sec), ρ_2^0 = 2500 kg/m^3, c_2 = 710 $m^2/(sec^2 \cdot deg)$.

The distance between the shock front and the wall was given at 3.05m, the wavelength at 0.45 m, the shock Mach number at 4.2. The accuracy of the computations was checked by a recomputation with diminished spacings in space and time.

The process of explosive wave reflection from a wall in the presence of an air-suspension layer is illustrated in Figs. 1 and 2; computed pressure (Fig. 1) and velocity (Fig. 2) profiles of the gas (continuous lines) and the particles (dotted lines) at a number of times. The computation was executed for a gas-suspension layer with the parameters l_s = 3 m, m = ρ_{20}/ρ_{10} = 2.1, d = 60 μm. The curve 0 (t = 0) characterizes the shock incident on the gas-suspension layer in a gas without particles (m = 0). Curves 1-9 correspond to t = 0.9, 2.8, 4.6, 5.5, 5.8, 6.9, 7.3, 8.3, 14.8 msec. The dashed and dash-dot lines in Fig. 1 illustrate a thermodynamically equilibrium (the space of very fine particles d → 0) and a frozen (no particle influence d → ∞) solution. The arrows show the direction of wave motion.

It is seen that the presence of the screening layer results in a noticeable transformation of the "triangular" wave incident on the wall: the wave becomes blurred, weaker and longer. In the case of a sufficiently strong explosive wave the process of its intersection with an obstacle can be divided provisionally into a stage of instantaneous (jumplike) elevation of the pressure on the wall, a stage of a successive smooth pressure rise, and a stage of its subsequent gradual drop to the initial value. The first is associated with reflection of the forward shock from the wall in the gas phase, the pressure there is hence raised abruptly, a reflected shock moving in the domain of the gas-suspension occurs. The stage of a smooth pressure rise on the wall is due to interaction of the incident and reflected nonstationary waves in the inhomogeneous gas-suspension flow. The reflected wave front here moves towards the two-phase stream, whose pressure and velocity ahead of the front grow smoothly at these times. In this connection the pressure both behind the reflected shock and in the whole zone of gas and particle parameter relaxation between the front and the wall increases gradually. The maximal value of the pressure behind the reflected wave is realized on the boundary of the relaxation zone near the wall where the flow is retarded.

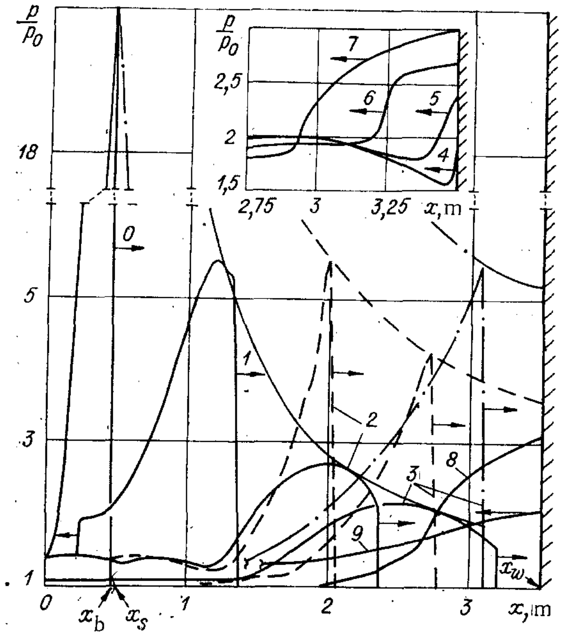

Fig. 1

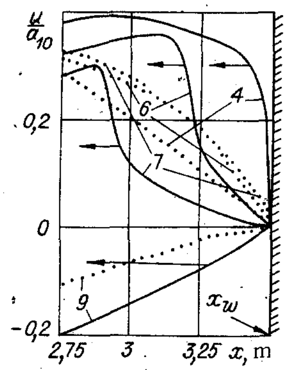

Fig. 2

Later interaction between the reflected compression wave and the rarefaction wave occurs with the result being the beginning of the third stage, the obstacle unloading stage. Diminution of the pressure thereon is accompanied by a flow inversion behind the reflected shock that was directed earlier towards the wall. The carrier initially, and then the disperse phase also, are entrained in the reverse motion from the wall. Heavy particles moving more slowly than the gas hinder its efflux from the wall, thereby increasing the time of excess pressure action on the obstacle.

It should be noted that the process of reflecting a "short" (explosive) shock from a wall in a gas-suspension (with a duration less or commensurate with the characteristic times of phase parameter equilibration) differs substantially from the "long" wave reflection process (with a duraction considerably exceeding the mentioned characteristic times). In particular, it differs radically from the stationary shock reflection process of infinite duration investigated in [13, 15]. Reverse motion of both phases from the obstacle, accompanied by a gradual diminution in the pressure at the wall is observed during explosive wave reflection from the wall. A reflected stationary wave occurs in the gas-suspension during reflection of a stationary compression wave, where the pressure is homogeneous in the zone of equilibrium phase parameters near the obstacle, while there is no gas and particle motion with respect to the wall [13, 15].

The influence of the particle screening layer on the law of pressure variation on the wall with time is illustrated in Fig. 3 by computed pressure "oscillograms." The curve 0 shows the law of pressure variation in the absence of suspended particles. Curves 1-3 characterize the pressure change on the wall when it is screened by a gas-suspension layer with the particle size 60 μm and thickness 3 m for different mass contents of the suspended phase (m = 0.3, 0.8, and 2.1, respectively). The curve 4 (compare with curve 3) shows how the pressure on the wall would change if the particle diameter in the gas-suspension layer m = 2.1 were quite small ($d \to 0$, a thermodynamically equilibrium approximation).

It is seen that in a "pure" gas and for small mass contents of particles in the layer $m \ll 1$ the pressure by the shock on the wall will reach its maximal value and then decrease smoothly. For large mass contents of the particles in the layer $m \sim 1$, after the first jump-like pressure rise on the wall at the time of shock arrival its further smooth rise is observed first and only then the subsequent diminution. In addition, as the particle concentration increases in the dust layer an increase in the characteristic time of shock action on the obstacle takes place. A comparison of curves 0, 3, 4 shows that the equilibrium (curve 0) and frozen (curve 4) gas-suspension flow diagrams are completely unsuitable for determining the laws of pressure variation on the wall during the incidence of explosive waves. Let us note that for long shocks the equilibrium scheme permits correct computation of the maximum steady value of the pressure on the wall although it is also unsuitable for

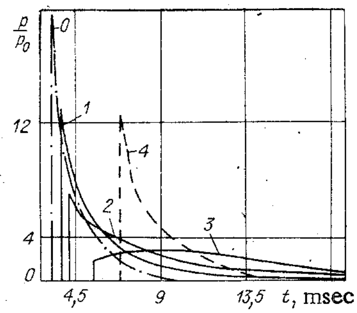

Fig. 3

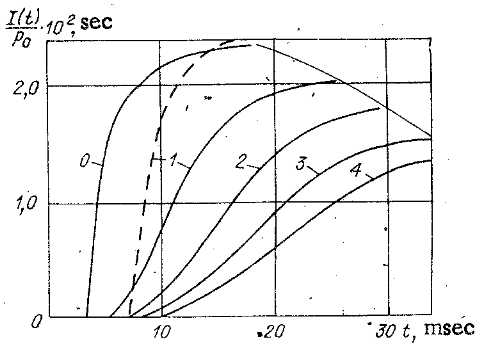

Fig. 4

an adequate description of the law of pressure rise with time in the initial stage of "diffuse" wave interaction with a wall.

3. Analysis of the Impulsive Action of a Shock in a Gas-Suspension on a Wall

We shall characterize the magnitude of the impulsive action of a gas flow with particles on a wall by the sum $I(t) = I_1(t) + I_2(t)$ [$I_1(t)$ is the impulse of the excess gas pressure and $I_2(t)$ the impulse of the particle velocity head]:

$$I_1(t) = \int_{t_*}^{t} (p_w - p_0)\, d\tau, \quad I_2(t) = \int_{t_*}^{t} \frac{\rho_{2,w} u_{2,w}^2}{2}\, d\tau,$$

where t_* is the characteristic time of the beginning of wave action on the obstacle, p_0 is the initial unperturbed pressure, p_w is the running presure on the wall behind the reflected wave, and $\rho_{2,w}$, $u_{2,w}$ are the mean density and flux velocity of the particles at the time of their interaction with the wall.

Shown as an example in Fig. 4 are the computational dependences of the impulse I(t) on a wall upon incidence of an explosive wave with M = 4.2 on a screening layer 3 m thick with different mass contents of the suspended particles of 60-μm diameter. Curves 1-4 (the solid lines) correspond to the suspension mass contents m = 2.1, 4.1, 6.2, and 8.3. Curve 0 illustrates the case of total absence of interphase interaction (computation within the framework of a "frozen" screening layer scheme). Curve 1 (dashed line) shows the change in impulse I(t) on the wall for a m = 2.1 particle mass content and d → 0 diameter (computation within the framework of the "thermodynamically equilibrium" screening layer scheme). The locus of maximal values of I(t) is shown approximately by the fine continuous line.

It is seen from Fig. 4 that as the particle mass content increases from 0-8 in the gas, a noticeably reduction (of ~2 times) is observed in the magnitude of the maximal impulsive action of the explosive wave on the wall. Computations show that the magnitude of the excess gas pressure impulse on the wall $I_1(t)$ is considerably greater, in all the cases considered than the impulse of the particle velocity head $I(t) \simeq I_1(t) \gg I_2(t)$, i.e., the contribution of of $I_2(t)$ to the quantity I(t) is negligible. Therefore, the disperse particles themselves do not directly influence the impulsive action of the shock on the obstacle, their influence appears as an action on the flow dynamics as a whole. It is seen from Fig. 4 (see curve 1) that the computation of the magnitude of the maximal impulsive action of a shock on an obstacle within the framework of the equilibrium model of a gas-suspension will exaggerate the maximal impulse on the wall by approximately 20%. This circumstance again illustrates the inapplicability of the equilibrium gas-suspension scheme for computation of explosive wave interaction with obstacles.

4. Influence of Governing Parameters of the Screening Layer on the Magnitude of the Maximal Pressure on the Wall

Certain integral results of investigating the influence of the extent of the dust zone as well as the particle mass content and size on the magnitude of the maximal pressure on the wall are represented in Figs. 5 and 6. Figure 5 illustrates the influence of the dust zone width l_s and the suspension mass content m on the magnitude of the maximal pressure on the

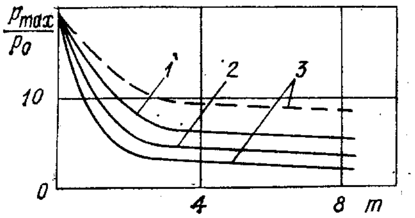

Fig. 5

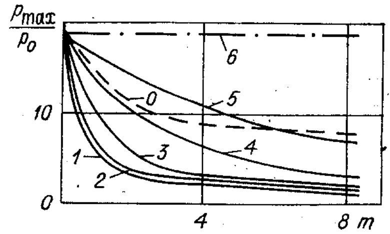

Fig. 6

obstacle. Curves 1-3 (solid lines) are dust zones of thickness 1-3 m, respectively, for a 60-μm particle diameter, the dashed line is the value of the maximal pressure on the wall for dust layers of 3 m extent, obtained by a computation by the thermodynamically equilibrium gas-suspension scheme. It is seen that an increase in the screening layer thickness results in a reduction in the maximal pressure on the wall. The most effective reduction in the maximal pressure (of 3-5 times) is achieved as m increases from 0 to 3. As m increases further, the tempo of the reduction in the maximal pressure drops noticeably. Other conditions being equal, a 1 m increase in l_s results in a 0.15-0.3 MPa reduction in the maximal pressure on the wall. It should be emphasized that a computation by the equilibrium scheme yields a noticeably exaggerated value of the maximal pressure on the obstacle.

Illustrated in Fig. 6 is the influence of the particle size d and their mass content m on the magnitude of the maximal pressure at the wall. Curves 1-5 correspond to the particle diameters 30, 60, 120, 240, and 480 μm. Curves 0 and 6 illustrate the thermodynamically equilibrium and frozen solutions, respectively. It is seen that as the particle size diminishes from 480-30 μm, the magnitude of the maximal pressure on the wall diminishes. The thermodynamically equilibrium solution yields a greater value of the maximal pressure on the wall than does the nonequilibrium solution with d = 30 μm.

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INFLUENCE OF THE INITIAL CHARACTERISTICS OF THE MEDIUM ON THE PARAMETERS OF THE REFLECTION OF SHOCK WAVES

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UDC 532.593

The passage of shock waves through solids can be accompanied by various physicochemical transformations. The results of a transformation depend on the change in the state of the medium under the shock-wave action, which is determined, in turn, not only by the intensity of the shock wave but also by the parameters of the initial state of the medium. The development of new phase transitions and chemical reactions [1-4], impact hardening of brittle alloys [5], the compression of solid and refractory powders [4, 6, 7], etc. become possible for certain combinations of the initial parameters.

Actual schemes of impact loading are such that the oblique reflection of shock waves from the interface between two media with different properties often occurs. In this connection it seems interesting to clarify how significant the influence of the change in the initial parameters of the medium on the reflection parameters may prove to be.

1. Statement of the Problem and Subjects of the Investigation

In the work we investigated only the region of regular regimes of reflection, since the flow structure in solids during irregular reflection has not yet been studied. In accordance with [8-10], the critical value of the angle of inclination of the incident wave at which the transition from the regular to the irregular regime of reflection occurs was taken as equal to the value for the upper limit of the region of existence of the regular regimes.

The paper is devoted to a numerical study of the influence of the initial characteristics of the medium and the loading parameters on the values of the critical angle φ^* and the pressure p_2 behind the reflected wave. In particular, the dependence of these parameters on the pressure p_1 in the incident wave and on the initial temperature T of the medium was studied in detail. In addition, we investigated the dependence of the pressure behind the reflected shock wave on the angle of incidence φ for different initial temperatures T. Data were obtained on the influence of the initial porosity of the metal on the value of the critical angle and on the pressure change during reflection.

Aluminum, copper, and tungsten were chosen as the subjects of the investigation. The choice was conditioned by the presence of reliable data on the equation of state in a wide region of variation of pressure and temperature; by the absence of phase transitions in the investigated region, allowing us to isolate in pure form the influence of the parameters of the initial state and to simplify the interpretation of the results obtained; by the considerable differences in the chosen media with respect to dynamic compressibility, initial density, and such parameters characterizing the change in the state of the substance under loading as the heat capacity and the volume expansion coefficient.

We consider the incidence of a plane shock wave AO onto a reflecting surface EF at an angle φ (Fig. 1). It is assumed that the boundary condition, consisting in the flow being parallel to the reflecting surface, can be satisfied by means of the reflected shock wave OB [11]. The flow in regions 0, 1, and 2 is assumed to be uniform, while the velocity of propagation of the shock wave AO relative to the undisturbed medium 0 is constant. The problem is analyzed in a coordinate system connected with the point O in which it is stationary.

2. Calculating Equations and Method of Solution

According to [11], the expression for the angle θ_1 of deviation of the stream by the incident shock wave has the form

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