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NUMERICAL STUDY OF THE ACTION OF A SHOCK WAVE ON AN OBSTACLE SCREENED BY A LAYER OF POROUS POWDER MATERIAL

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Currently for a number of branches of modern technology there is a very important problem of mathematical modeling for the process of shock wave operation on an obstacle shielded by a layer of loose material. In particular the requirement of solving this problem is encountered in pneumatic transport of loose materials with creation of a system for explosion protection of trunk lines, in powder technologies, in explosive processing of materials, and in safety techniques with analysis of the efficiency of protecting units screened by free-flowing layers.

The problem of studying the effect of porous shields on the reaction of shock waves with a rigid surface has been considered in [1-4] where it is shown that the maximum pressure amplitude at an obstacle shielded by layer of porous material may exceed considerably the pressure of a normal reflected shock wave from the wall of an obstacle in the absence of a porous layer. In [1, 2] in order to explain the behavior of the shielding layers of porous shields of the polyurethane type (solid porous coating with a porosity of ~97%) with passage through the layer of shock waves with Mach number ~2 a very simple model of an effective gas is used. In [3] the effect is studied of a layer of polyurethane foam on the maximum excess pressure behind the shock wave reflected from the wall using in contrast to [1, 2] models describing shield porosity: a shielding porous layer is represented by an equivalent mechanical system with one degree of freedom from a load of mass m and a combination of ideally plastic and elastic elements. Results are given in [4] for an experimental study of the parameters of shock waves reflected from a solid wall coated by a layer of porous loose material. A similar model of a porous specimen is used in order to describe the behavior of the pressure amplitude at an obstacle.

A detailed analysis is provided in this work for the process of shielding an obstacle by a layer of loose material within the scope of a two-phase model of powder material.

1. Basic Equations. In order to describe movement of a gas and porous powder material represented by a mixture of solid particles in contact with each other and gas in pores

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assumptions known in the mechanics of dispersed solid multiphase materials are adopted [5]. In addition it is assumed that dispersed particles of powder material are an assembly of uncompressed deformable noncrushing monodispersed inert particles of spherical shape; a change in internal energy of the powder material caused by the work of the force of interphase friction is accomplished entirely through the gas phase. With these assumptions assuming the possibility of a difference in gases in different flow regions the equations for nonstationary plane unidimensional movement of a powder material are written in the form [5, 6]

$$\frac{\partial\rho_{11}}{\partial t}+\frac{\partial\rho_{11}v_1}{\partial x}=0,\quad \frac{\partial\rho_{12}}{\partial t}+\frac{\partial\rho_{12}v_1}{\partial x}=0,\quad \frac{\partial\rho_2}{\partial t}+\frac{\partial\rho_2 v_2}{\partial x}=0,$$
$$\frac{\partial\rho_1 v_1}{\partial t}+\frac{\partial\rho_1 v_1^2}{\partial x}+\alpha_1\frac{\partial p}{\partial x}=-\alpha_1 F_{12},$$
$$\frac{\partial\rho_2 v_2}{\partial t}+\frac{\partial\rho_2 v_2^2}{\partial x}+\alpha_2\frac{\partial p}{\partial x}-\frac{\partial\sigma_{2*}^{11}}{\partial x}=\alpha_1 F_{12},$$
$$\frac{\partial\rho_2 u_{2T}}{\partial t}+\frac{\partial\rho_2 u_{2T}v_2}{\partial x}-\xi_{2T}\sigma_{2*}^{11}\frac{\partial v_2}{\partial x}=Q_{12},$$
$$\frac{\partial\rho_2 u_{2p}}{\partial t}+\frac{\partial\rho_2 u_{2p}v_2}{\partial x}-(1-\xi_{2T})\,\sigma_{2*}^{11}\frac{\partial v_2}{\partial x}=0, \tag{1.1}$$
$$\frac{\partial}{\partial t}(\rho_1E_1+\rho_2E_2)+\frac{\partial}{\partial x}(\rho_1E_1v_1+\rho_2E_2v_2+p(\alpha_1v_1+\alpha_2v_2)-\sigma_{2*}^{11}v_2)=0,$$
$$\rho_i=\rho_i^0\alpha_i,\quad E_i=u_i+0{,}5v_i^2\quad (i=1,2),\quad \alpha_1+\alpha_2=1,$$
$$\rho_{1j}=\rho_{1j}^0\alpha_{1j},\quad E_{1j}=u_{1j}+0{,}5v_1^2\quad (j=1,2),\quad u_2=u_{2T}+u_{2p},$$
$$\rho_1=(1-\varepsilon)\,\rho_{11}+\varepsilon\rho_{12},\quad \rho_1^0=\rho_{11}^0(1-\varepsilon)+\varepsilon\rho_{12}^0,$$
$$\alpha_1=(1-\varepsilon)\,\alpha_{11}+\varepsilon\alpha_{12},\quad u_1=(1-\varepsilon)\,u_{11}+\varepsilon u_{12},\quad p=(1-\varepsilon)\,p_{11}+\varepsilon p_{12}.$$

Here subsequently lower indices 1 and 2 relate to gas and dispersed gas parameters, respectively; lower indices 11 and 12 relate to the parameters of two different nonmixing gases localized in space; ε is a parameter taking the value zero in the region of space occupied by the first gas and one in the region of space occupied by the second gas; ρ, ρ^0, α, v, u, E are average and true density, volume content, mass velocity, specific internal and total energy for the same or another component of the mixture; p is gas phase pressure; σ_{2*}^{11} is hypothetical stress (longitudinal "pressure" [5]) in a porous powder material caused by natural deformation of incompressible particles; d is particle diameter; F_{12} and Q_{12} are force of interphase friction and the intensity of heat transfer from the gas to the dispersed phase in a unit volume of mixture; u_{2T} and u_{2p} are thermal and elastic components of the internal energy of powder particles; and ξ_{2T} is a factor determining the part of the work of intergranular stress converted into thermal energy of the solid phase u_{2T} $(0\leqslant\xi_{2T}\leqslant 1)$.

Set of quasilinear differential Eqs. (1.1), which describes the combined nonequilibrium movement of the gas and dispersed phase of powder material, is supplemented by equations of state for ideal calorifically perfect gases and incompressible solid particles:

$$p_{1j}=(\gamma_{1j}-1)\,\rho_{1j}^0u_{1j},\quad u_{1j}=c_{1j}T_1\quad (\gamma_{1j},\ c_{1j}\equiv\text{const}),$$
$$\rho_2^0=\text{const},\quad u_2=c_2T_2\quad (c_2\equiv\text{const}) \tag{1.2}$$

[γ_{1j} and c_{1j} are index of the adiabat and specific heat capacity with a constant volume of the j-th gas (j = 1, 2), T_1 and T_2 are gas and dispersed particle temperatures].

The equation of state for a porous skeleton of powder material describing interparticle interaction is prescribed on the basis of data in [7] in the following form

$$\sigma_{2*}^{11}=\begin{cases}-\rho_2^0\alpha_{10}a_{20}^2\left(\dfrac{\alpha_{10}}{\alpha_1}-1\right) & (\alpha_1<\alpha_{10}\leqslant\alpha_{1p}),\\ -\rho_2^0\alpha_{1p}a_{2p}^2\left(\dfrac{\alpha_{1p}}{\alpha_1}-1\right) & (\alpha_1<\alpha_{1p}\leqslant\alpha_{10}),\\ 0 & (\text{in other cases})\end{cases} \tag{1.3}$$
$$(a_{20}=a_{2p}+k\,(\alpha_{1p}-\alpha_{10}),\ \alpha_{10}\leqslant\alpha_{1p}).$$

Here α_{10} and a_{20} are porosity and sound velocity in powder material in the initial condition; α_{1p} and a_{2p} are porosity and speed of sound in powder material in a free-flowing condition; k is an empirical constant specifying the growth in sound velocity in a compacted specimen of porous powder material [8].

The equation of state adopted in the form of (1.3) for the dispersed solid phase describes the change in interparticle stress in powder material with compression of it and unloading by a scheme for a nonlinearly elastic body. Within the scope of this scheme the heat inflow equation for the elastic component of internal energy for the dispersed phase (1.1) is solved analytically, and

$$u_{2p} = -(1-\xi_{2T})\, a_{20}^2 \alpha_{10} \left[\frac{\alpha_{10}-\alpha_1}{1-\alpha_1} + \alpha_{10} \ln \frac{\alpha_1 (1-\alpha_{10})}{\alpha_{10}(1-\alpha_1)}\right] \quad (\alpha_1 < \alpha_{10} \leqslant \alpha_{1p}),$$

$$u_{2p} = -(1-\xi_{2T})\, a_{2p}^2 \alpha_{1p} \left[\frac{\alpha_{1p}-\alpha_1}{1-\alpha_1} + \alpha_{1p} \ln \frac{\alpha_1 (1-\alpha_{1p})}{\alpha_{1p}(1-\alpha_1)}\right] \quad (\alpha_1 < \alpha_{1p} \leqslant \alpha_{10}), \tag{1.4}$$

$$u_{2p} = 0 \qquad \text{(in other cases)}.$$

The intensity of interphase friction and heat exchange is prescribed on the basis of relationships in [5, 6]

$$F_{12} = \frac{3}{4}\frac{\alpha_2}{d} C_d \rho_1^0 |v_1 - v_2| (v_1 - v_2),$$

$$Q_{12} = \frac{6\alpha_2}{d^2} \lambda_1 \mathrm{Nu}_{12} (T_1 - T_2), \quad \lambda_1 = (1-\varepsilon)\lambda_{11} + \varepsilon\lambda_{12}, \tag{1.5}$$

where C_d is friction coefficient; Nu_{12} is gas phase Nusselt number; d is dispersed particle diameter; and λ_1, λ_{1j} are thermal conductivity coefficients for the gas phase as a whole and for the j-th gas individually (j = 1, 2).

The friction coefficient is described by an empirical relationship [9]

$$C_d = \begin{cases} C_d^{(1)} = \dfrac{24}{\mathrm{Re}_{12}} + \dfrac{4{,}4}{\sqrt{\mathrm{Re}_{12}}} + 0{,}42 & (\alpha_1 \geqslant 0{,}92), \\ C_d^{(2)} = \dfrac{4}{3\alpha_1}\left(1{,}75 + \dfrac{150(1-\alpha_1)}{\alpha_1 \mathrm{Re}_{12}}\right) & (\alpha_1 \leqslant 0{,}55), \\ \dfrac{(0{,}92-\alpha_1)C_d^{(2)} + (\alpha_1 - 0{,}55)C_d^{(1)}}{0{,}37} & (0{,}55 < \alpha_1 < 0{,}92) \end{cases} \tag{1.6}$$

$$(\mathrm{Re}_{12} = \rho_1^0 |v_1 - v_2|\, d/\mu_1, \quad \mu_1 = (1-\varepsilon)\mu_{11} + \varepsilon\mu_{12}).$$

Here Re_{12} is Reynolds number for relative gas and powder material particle movement; μ_1 and μ_{12} are dynamic viscosity of the gas phase as a whole and the j-th gas individually; $C_d^{(1)}$ is aerodynamic resistance factor for single spherical particles; and $C_d^{(2)}$ is the friction coefficient for spherical particles in free-flowing powders obtained in experiments [10].

In order to determine Nusselt number an empirical relationship is used [11]

$$\mathrm{Nu}_{12} = \begin{cases} 2 + 0{,}106\,\mathrm{Re}_{12}\mathrm{Pr}^{1/3}, & \mathrm{Re}_{12} \leqslant 200, \\ 2{,}274 + 0{,}6\mathrm{Re}_{12}^{2/3}\mathrm{Pr}^{1/3}, & \mathrm{Re}_{12} > 200 \end{cases} \tag{1.7}$$

$$(\mathrm{Pr} = \gamma_1 c_1 \mu_1/\lambda_1, \quad \gamma_1 = (1-\varepsilon)\gamma_{11} + \varepsilon\gamma_{12}),$$

where Pr is Prandtl number; and γ_1 and γ_{1j} are indices of the adiabat for the gas phase as a whole and the j-th gas individually.

2. Statement of the Problem. Applied to experimental conditions [4] the following problem is considered. In the initial instant of time t = 0 in the high-pressure chamber (HPC) region of a shock tube ($0 \leqslant x \leqslant x_*$) there is compressed gas (helium); the low-pressure chamber (LPC) region ($x_* < x \leqslant x_w$) is partly ($x_* < x < x_{**}$) filled with undisturbed gas (air) and partly ($x_{**} \leqslant x \leqslant x_w$) with a layer of free-flowing powder material which is a mixture of particles (polystyrene granules) in contact and gas (air) filling the pore space (Fig. 1). At the end of the LPC ($x = x_w$) there is a pressure sensor D. It is required to study the process of reaction of an air shock wave, forming in the LPC as a result of a breakdown of the initial discontinuity in the system of compressed HPC gas—LPC gas, with a layer of powder ($x_{**} \leqslant x \leqslant x_w$) and an obstacle ($x = x_w$) at instant of time t > 0 and to compare the solution obtained with experimental data.

The initial conditions of the formulated problem have the form in region $0 \leqslant x \leqslant x_*$ (compressed helium)

$$p(x,0) = p_*, \quad \rho_{11}^0(x,0) = 0, \quad \rho_{12}^0(x,0) = \rho_1(x,0) = \rho_{1*}, \quad T_1(x,0) = T_{1*},$$

$$v_1(x,0) = 0, \quad \rho_2(x,0) = \alpha_2(x,0) = \sigma_{2*}^{11}(x,0) = T_2(x,0) = v_2(x,0) = 0; \tag{2.1}$$

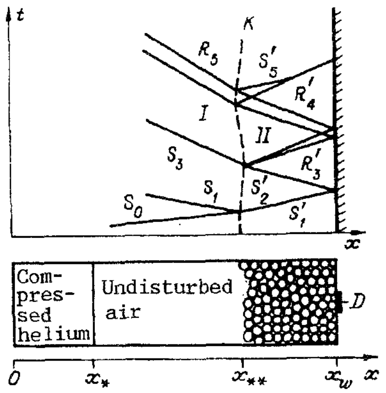

Fig. 1

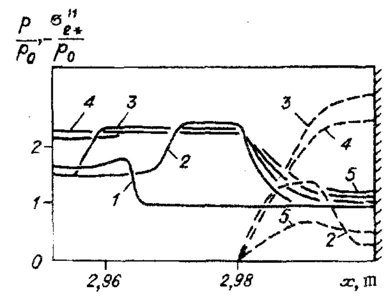

Fig. 2

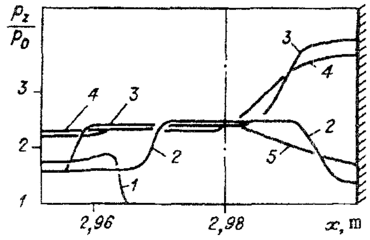

Fig. 3

in region $x_* < x < x_{**}$ (undisturbed air)

$$p(x, 0) = p_0, \quad \rho_{11}^0(x, 0) = \rho_1(x, 0) = \rho_{10}^0,$$
$$\rho_{12}^0(x, 0) = 0, \quad T_1(x, 0) = T_{10}, \quad v_1(x, 0) = 0, \tag{2.2}$$
$$\rho_2(x, 0) = \alpha_2(x, 0) = \sigma_{2*}^{11}(x, 0) = T_2(x, 0) = v_2(x, 0) = 0;$$

and in region $x_{**} \le x \le x_w$ (free-flowing layer of powder)

$$p(x, 0) = p_0, \quad \rho_{11}^0(x, 0) = \rho_{10}^0, \quad \rho_{12}^0(x, 0) = 0, \quad \rho_1(x, 0) = (1 - \alpha_{20})\rho_{10}^0,$$
$$T_1(x, 0) = T_{10}, \quad v_1(x, 0) = 0, \quad \alpha_2(x, 0) = \alpha_{20}, \quad \rho_2(x, 0) = \alpha_{20}\rho_2^0, \tag{2.3}$$
$$\sigma_{2*}^{11}(x, 0) = 0, \quad T_2(x, 0) = T_{20}, \quad v_2(x, 0) = 0.$$

The boundary conditions of the problem are prescribed as follows. At the left-hand ($x = 0$) and right-hand ($x = x_w$) boundaries of the calculation region corresponding to the ends of the shock tube conditions are laid down for equality to zero of gas and powder particle velocities:

$$v_1(0, t) = v_1(x_w, t) = 0, \quad t \geqslant 0,$$
$$v_2(0, t) = v_2(x_w, t) = 0, \quad t \geqslant 0. \tag{2.4}$$

Numerical integration of set of Eqs. (1.1)-(1.7) with initial (2.1)-(2.3) and boundary (2.4) conditions was carried out by the method of coarse particles [12, 13]. Calculations were performed using the following values of thermodynamic parameters of the phases:

1) in region $0 \leqslant x \leqslant x_*$ for helium $p_* = 5$ MPa, $\rho_{1*} = 8.2$ kg/m^3, $T_{1*} = 293$ K, $\gamma_{12} = 1.67$, $c_{p12} = 5190$ m^2/(sec^2·K), $\mu_{12} = 1.95 \cdot 10^{-5}$ kg/(m·sec), $\lambda_{12} = 0.149$ kg·m/(sec^3·K);

2) in region $x_* < x < x_{**}$ for air $p_0 = 0.1$ MPa, $\rho_{10}^0 = 1.19$ kg/m^3, $T_{10} = 293$ K, $\gamma_{11} = 1.4$, $c_{p11} = 1004$ m^2/(sec^2·K), $\mu_{11} = 1.81 \cdot 10^{-5}$ kg/(m·sec), $\lambda_{11} = 0.0258$ kg·m/(sec^3·K);

3) in region $x_{**} \leqslant x \leqslant x_w$ for air $p_0 = 0.1$ MPa, $\rho_{10}^0 = 1.19$ kg/m^3, $T_{10} = 293$ K, $\gamma_{11} = 1.4$, $\alpha_{10} = 0.52$, $c_{p11} = 1004$ m^2/(sec^2·K), $\mu_{11} = 1.81 \cdot 10^{-5}$ kg/(m·sec), $\lambda_{11} = 0.0258$ kg·m/(sec^3·K);

4) in region $x_{**} \leqslant x \leqslant x_w$ for polystyrene particles $\rho_2^0 = 1060$ kg/m^3, $\alpha_{20} = 0.48$, d = 200 µm, $T_{20} = 293$ K, $c_2 = 1300$ m^2/(sec^2·K), $a_{20} = 420$ m/sec.

Values of 0.01, 2.98, and 3 m were taken for x_*, x_{**}, and x_w, respectively.

3. Some Results. A qualitative picture of the wave interaction of an incident air shock wave with a layer of powder (if it is considered as an "effective" material) and an obstacle is shown in Fig. 1 where region I is occupied by air, II is occupied by effective material relating to a layer of powder, K is the boundary of the layer, S_0 is incident air shock wave, S_i' and R_i' are compression and rarefaction waves in the layer shielding the obstacle which arise after reaction of shock wave S_0 with contact surface K (the number 1 indicates the sequence of wave formation in the layer as a result of reaction of waves with the obstacle and the boundary of the layer K), S_1, S_3, and R_5 are shock waves and rarefaction waves in air which form as a result of reaction of waves in the layer with its boundary K.

Thus, as can be seen from Fig. 1 if a layer of powder shielding an obstacle is represented as an effective material, then the action of the incident air shock wave on the obstacle will be governed by reaction of compression and rarefaction waves with the obstacle arriving from the shielding layer. It should be noted that this representation of a layer shielding an obstacle (see also [1, 2]) does not reflect features of powder material loading and unloading connected with the two-phase nature of the powder layer: the rapid nonequilibrium nature of the phases, nonconformity of stresses in the powder skeleton and in the pore gas, etc.

We turn to considering numerical solutions obtained within the scope of the general system of nonequilibrium two-phase movement of gas and powder particles.

Presented in Fig. 2 are curves for gas pressure (solid lines) and effective intergranular pressure of powder particles (broken lines) at instants of time 5.89, 5.97, 6.0, 6.04, 6.08 msec (curves 1-5, respectively). The broken-dotted line shows the contact boundary of the air–powder layer. It can be seen that as a result of reaction of an air shock wave (curve 1) with a layer of powder in the air region a shock wave is reflected, in the region of the powder material gas filtering through powder pores leads to movement of particles which in contact with each other form a compression wave in the solid skeleton (curves 2). On reaction of the compression wave in the powder with the obstacle (rigid wall) in the region of the shielding layer a compression wave is reflected propagating through powder particles (curve 3), and here pressure at the obstacle increases markedly.

As a result of reaction of a compression wave in the powder with the boundary of the layer a weak shock wave passes into the gas region, and in the powder material region a rarefaction wave propagates (curves 4) which reduces pressure at the obstacle. The subsequent wave process in the gas and in the shielding layer is governed by reaction of compression and rarefaction waves with the boundary of the layer and the obstacle, and pressure at the wall increases or decreases correspondingly on reaction of a compression or rarefaction wave with the obstacle (curves 4, 5). It is noted that the wave picture in the shielding powder layer is governed by compression and rarefaction waves which propagate through the solid powder phase, and gas continues to filter through the pores continuously increasing pressure at the obstacle (solid lines in the powder layer region).

Given in Fig. 3 is the distribution of gas pressure p and total stress in the powder material $p_\Sigma = p - \sigma_{2*}^{11}$. The instants of time and notation are the same as in Fig. 2. It can be seen from Fig. 3 that the qualitative picture of wave processes in the powder (as an effective material) provided in Fig. 1 adequately explain the wave picture in the powder layer and gas. As noted above, the main contribution to the wave behavior of powder material is given by the intergranular pressure of particles σ_{2*}^{11} (see Fig. 2).

As a result of reaction of an air shock wave with the boundary of the layer gas penetrating into the powder is retarded around particles simultaneously drawing them into movement. In view of the considerable inertia of particles their movement velocity is low (~2 m/sec), although it is sufficient for powder deformation caused by movement of particles leading to a marked increase in intergranular pressure. There is almost no movement of the layer boundary, which is also noted in experiments in [4]. This is explained by the low movement velocity of particles and the fact that after each reaction of compression and rarefaction waves from the boundary of the layer propagating within the powder the contact boundary changes the direction of movement into an opposite one (see Fig. 1).

Given in Fig. 4 is an oscillogram of pressure at the obstacle in the case of absence of a shielding layer. The change of pressure at the obstacle is caused by reaction of an air shock wave (curve 1 in Fig. 2) with an absolutely rigid wall. The oscillogram of pressure at the wall has a flat triangular profile. This is explained by the fact that the incident shock wave at the obstacle by weakening rarefraction waves passing from the left-hand end of the shock tube acquires a triangular form and it is reflected from the obstacle in the form of a triangular-shaped shock wave. Thus, the oscillogram of pressure from a sensor placed at the obstacle has a uniformly decreasing form with a maximum equal to ~0.28 MPa.

Presented in Fig. 5 are oscillograms of pressure at the obstacle with shielding of it by a layer of free-flowing powder. Shown in Fig. 5a is the picture obtained by calculation for the change in gas pressure at the obstacle (solid line) and the intergranular pressure of particles (broken line). Shown in Fig. 5b is the calculated (solid line) and experimental [4] (broken-dotted line) oscillograms for total stress at the obstacle.

As can be seen from Fig. 5b, the nature of change in pressure at the obstacle with shielding by a layer of free-flowing material is markedly different from the case of no shielding layer: it is not uniform with rapidly fading oscillations. Here the maximum

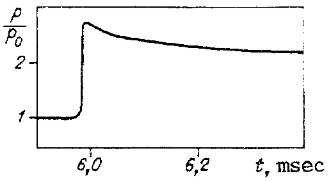

Fig. 4

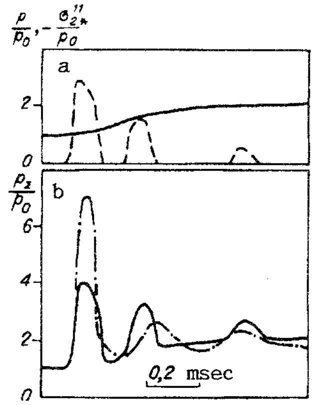

Fig. 5

pressure at the wall markedly exceeds the maximum pressure in the case of no free-flowing layer and in calculations it is ~0.4 MPa. Behind the compression phase at the obstacle surface there follows a rarefraction phase in which pressure is reduced to ~0.125 MPa. The nonuniform behavior of pressure at the end of the shock tube, as was shown above, is explained by reaction of compression and rarefaction waves with the obstacle and the surface layer of the powder.

From Fig. 5a it can be seen that the change in pressure at the wall caused by gas pressure in powder pores (solid line) is governed by gas filtration through the powder layer and it has a continuously increasing form. "Bursts" in pressure lasting ~0.15 msec are determined by compression and unloading of the solid skeleton of the powder layer, and their duration depends on the propagation rate for waves in the shielding layer.

From comparison of the calculated and experimental oscillograms for pressure at the LPC end it is possible to conclude qualitative agreement of the calculated solution with experimental data. Quantitative differences occur for the oscillation amplitude of the pressure sensor placed on the obstacle; in particular, the difference in maximum pressure at the wall obtained by numerical calculation from that measured in an experiment is ~50%. This is apparently connected with the fact that in prescribing polystyrene powder parameters (in particular sound velocity in free-flowing powder) some rules of these parameters typical for free-flowing materials were used. In addition, the maximum load on the obstacle depends to a considerable extent on the initial state of the powder material: whether it is in a limiting packing condition or not. As additional calculations show, if the initial powder porosity α_{10} is greater than the free-flowing porosity α_{1p}, then with passage of a shock wave in a layer of powder material considerable particle velocities are realized and correspondingly there is a greater intergranular pressure compared with the case in question, and the amplitude of maximum pressure at the obstacle may markedly exceed the value obtained. Unfortunately the relationship between α_{10} and α_{1p} is not specified in [4] and therefore in the calculation it was assumed that $\alpha_{1p} = \alpha_{10}$.

Thus, the results of the numerical study performed point to the suitability of the two-velocity model (with two pressures of gas mixture and solid particles in contact) for describing the process of shielding an obstacle with free-flowing layers. In addition, it is established for the case in question of shielding an obstacle by a powder layer the contribution of the thermal nonequilibrium of phases in view of the considerable mass of powder particles is negligibly small (the difference in solutions with consideration of and without taking account of interphase heat exchange does not exceed ~1%). The variation in parameter ξ_{2T} in the range from 0 to 1 also does not have a marked effect on the process of shielding an obstacle by a layer of powder material.

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