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NUMERICAL STUDY OF INITIAL PULSED MOTION OF A POWDER LAYER IN A DUCT UNDER THE ACTION OF A COMPRESSED GAS

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One-dimensional plane pulsed joint motion of a gas phase and a disperse phase in the presence of friction of the latter against the duct walls are studied numerically using the model of a heterogeneous medium. It is established that two qualitatively different regimes of motion are possible, depending on the initial conditions in a high-pressure chamber and the value of the friction factor. It is found that the powder exit velocity is self-similar with respect to friction.

The new pulsed technology for elimination of accidents (fire extinguishing, shielding, etc.) is based on the ejection of working powder media by a pressurized gas. In this connection, the problem of studying the physical pattern and qualitative characteristics of the dynamics of gas and disperse phases arises.

The process of powder ejection by a compressed gas was studied numerically by Ivandaev et al. [1] using a two-velocity, two-temperature, two-stress model ignoring friction forces. Some experimental data and results of numerical simulations for the one-dimensional one-flow pulsed motion of a gas-disperse mixture are presented by Zakhmatov [2]. It is noted [2] that the initial calculated velocity of the powder is systematically (up to 35%) higher than the experimental value. If the kinetic energy (see [2]) additionally imparted to powder particles in the rarefaction wave is ignored, this difference should be even larger. In our experiments, performed by a scheme similar to the one in [2], we detected that after pulsed ejection of a high-pressure gas under a layer of a disperse medium (quartz sand of moderate size) there is a characteristic delay of motion of the front edge of the layer. The delay is an order of magnitude larger than the estimate in [2] of the time of arrival of a shock wave and depends appreciably on the characteristic radius of the dispersed particles. It should be noted that in dynamic uniaxial loading of a powder placed in a rigid case (duct), a sharp decay of the solid-phase pressure in the depth of the specimen is observed [3]. This fact indicates the significant effect of friction of the particles against the duct walls. Below, we propose a mathematical model and study the motion of a powder layer numerically taking into account the friction between the particles and the duct walls.

Basic Equations. For a mathematical description of the joint motion of a gas and powder particles, we adopt the well-known assumptions of the dynamics of multiphase media [1–4]: the particle sizes are many times the molecular-kinetic dimensions and many times smaller than the distances at which the parameters of the mixture change appreciably, the mixture is monodisperse, there are no fragmentation, aggregation, and formation of new particles, the gas is ideal and calorifically perfect, viscosity and thermal conductivity are manifested only in interphase interaction processes, and gravity is ignored.

The duct is immovable. The intensities of interphase heat transfer and friction are proportional to the interfaces. Hence, because the surface area of the duct wall is much smaller than the total surface of the dispersed particles, the force and thermal interaction of the gas with the walls can be neglected. The friction force of the disperse phase per unit area of the duct is assumed to be a function of the effective stress of the

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disperse phase $\theta(\sigma_{2*}^{11})$ [3]. In addition, it is assumed that there is no heat transfer between the particles and the duct walls. The validity of this assumption for the problem considered below was tested by comparison of calculation results for the following two cases: 1) the total heat generated by the friction forces is transferred to the particles; 2) there is no heat release (the corresponding terms are eliminated from equations). The results given below for these two cases differ by about 1%. Variations of parameters along the duct cross section is ignored.

Under the above assumptions, the equations of plane one-dimensional motion of the mixture taking into account the inertia effects in flow around the particles [4] take the form

$$\frac{\partial \rho_i}{\partial t} + \frac{\partial \rho_i v_i}{\partial x} = 0, \quad \frac{\partial \rho_1 v_1}{\partial t} + \frac{\partial \rho_1 v_1^2}{\partial x} + \beta_1 \frac{\partial p}{\partial x} - (1-\beta_2)\frac{\partial \sigma_{2*}^{11}}{\partial x} = -\beta_3 F_\mu - (1-\beta_2)\Theta(\sigma_{2*}^{11}),$$

$$\frac{\partial \rho_2 v_2}{\partial t} + \frac{\partial \rho_2 v_2^2}{\partial x} + (1-\beta_1)\frac{\partial p}{\partial x} - \beta_2 \frac{\partial \sigma_{2*}^{11}}{\partial x} = \beta_3 F_\mu - \beta_2 \Theta(\sigma_{2*}^{11}),$$

$$\frac{\partial \rho_2 u_{2T}}{\partial t} + \frac{\partial \rho_2 u_{2T} v_2}{\partial x} - \xi_{2T}\sigma_{2*}^{11}\frac{\partial v_2}{\partial x} = Q + \Theta(\sigma_{2*}^{11}) v_2,$$

$$\frac{\partial \rho_2 u_{2p}}{\partial t} + \frac{\partial \rho_2 u_{2p} v_2}{\partial x} - (1-\xi_{2T})\sigma_{2*}^{11}\frac{\partial v_2}{\partial x} = 0, \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho_1 E_1 + \rho_2 E_2) + \frac{\partial}{\partial x}(\rho_1 E_1 v_1 + \rho_2 E_2 v_2 + p(\alpha_1 v_1 + \alpha_2 v_2) - \sigma_{2*}^{11} v_2) = 0,$$

$$\rho_i = \rho_i^0 \alpha_i \quad (i = 1, 2), \quad E_i = u_i + (1/2)v_i^2, \quad \alpha_1 + \alpha_2 = 1, \quad u_2 = u_{2T} + u_{2p},$$

$$\beta_1 = \frac{\alpha_1(2 + \chi_m \rho_1^0/\rho_2^0)}{2 + \chi_m(\alpha_2 + \alpha_1\rho_1^0/\rho_2^0)}, \qquad 0 \leqslant \xi_{2T} \leqslant 1,$$

$$\beta_2 = \frac{2 + \chi_m \alpha_2}{2 + \chi_m(\alpha_2 + \alpha_1\rho_1^0/\rho_2^0)}, \qquad \beta_3 = \frac{2}{2 + \chi_m(\alpha_2 + \alpha_1\rho_1^0/\rho_2^0)}.$$

Here and below, the subscripts 1 and 2 refer to the parameters of the gas and disperse phase, respectively, and the superscript 0 refers to true values of density. The normalized density, velocity, internal and total energies of unit mass, and the volumetric fraction of the ith phase are denoted by ρ_i, v_i, u_i, E_i, and α_i, respectively, p and σ_{2*}^{11} are the gas-phase pressure and the fictitious stress in the porous powder medium, u_{2T} and u_{2p} are the thermal and elastic components of the internal energy of the powder particles, F_μ, Q, and $\Theta(\sigma_{2*}^{11})$ are the viscous component of the interphase interaction force, the rate of heat exchange between the gas and the particles, and the friction of the powder layer against the duct walls, normalized to a unit volume of the mixture, ξ_{2T} is a factor that determines the part of the intergranular-stress work converted to the thermal energy of the solid phase [1], χ_m is a factor that allows for the effect of nonsingularity and nonsphericity of the particles on the attached-mass forces ($\chi_m = 1$ for spherical particles), and x and t are the Eulerian coordinate and time, respectively.

System (1) is supplemented by the equations of state for an ideal, calorifically perfect gas, the porous "frame" of a powder medium [5], and incompressible solid particles:

$$p = (\gamma_1 - 1)\rho_1^0 u_1, \qquad u_1 = c_v T_1, \qquad u_{2T} = c_2 T_2, \qquad \gamma_1,\ c_v,\ c_2,\ \rho_2^0 \equiv \text{const},$$

$$\sigma_{2*}^{11} = \begin{cases} -\rho_2^0 \alpha_{10} a_{20}^2(\alpha_{10}/\alpha_1 - 1), & \alpha_1 < \alpha_{10} \leqslant \alpha_{1p}, \\ -\rho_2^0 \alpha_{1p} a_{2p}^2(\alpha_{1p}/\alpha_1 - 1), & \alpha_1 < \alpha_{1p} \leqslant \alpha_{10}, \\ 0 \quad \text{otherwise}, \end{cases}$$

$$a_{20} = a_{2p} + k(\alpha_{1p} - \alpha_{10}), \qquad \alpha_{10} \leqslant \alpha_{1p}.$$

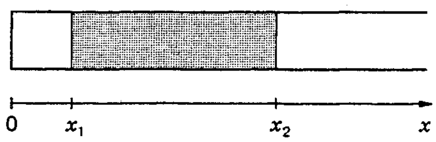

Fig. 1

Here T_1 and T_2 are the gas and particle temperatures, respectively, γ_1 is the adiabatic exponent, c_v and c_2 are the specific heat of the gas with constant volume and the specific heat of the particles, respectively, α_{10} and a_{20} are the porosity and speed of sound, respectively, in the powder medium in the initial state, α_{1p} and a_{2p} are the porosity and speed of sound, respectively, in the powder medium in the duct, and k is an empirical constant that characterizes the increase in the speed of sound in a compressed powder medium [6].

The rates of interphase friction and heat exchange are specified by the following relations [4, 7, 8]:

$$F_\mu = (3/8)(\alpha_2/r)C_\mu \rho_1 w_{12}|w_{12}|, \qquad w_{12} = v_1 - v_2,$$

$$C_\mu = \begin{cases} C_\mu^{(1)} = 24/\mathrm{Re}_{12} + 4.4/\mathrm{Re}_{12}^{1/2} + 0.42, & \alpha_2 \leqslant 0.08, \\ C_\mu^{(2)} = (4/(3\alpha_1))(1.75 + 150\alpha_2/(\alpha_1 \mathrm{Re}_{12})), & \alpha_2 \geqslant 0.45, \\ ((\alpha_2 - 0.08)C_\mu^{(2)} + (0.45 - \alpha_2)C_\mu^{(1)})/0.37, & 0.08 < \alpha_2 < 0.45, \end{cases}$$

$$Q = (3/2)(\alpha_2/r^2)\lambda_1 \mathrm{Nu}_1 (T_1 - T_2),$$

$$\mathrm{Nu}_1 = \begin{cases} 2 + 0.106\,\mathrm{Re}_{12}\mathrm{Pr}_1^{1/3} & (\mathrm{Re}_{12} \leqslant 200), \\ 2.27 + 0.6\,\mathrm{Re}_{12}^{0.67}\mathrm{Pr}_1^{1/3} & (\mathrm{Re}_{12} > 200), \end{cases} \qquad \mathrm{Re}_{12} = \frac{2r\rho_1^0 w_{12}}{\mu_1}, \quad \mathrm{Pr}_1 = \frac{c_v \gamma_1 \mu_1}{\lambda_1}.$$

Here Re_{12}, Nu_1, and Pr_1 are the Reynolds, Nusselt, and Prandtl numbers, C_μ, μ_1, and λ_1 are the interphase-friction factor, dynamic viscosity, and thermal conductivity for the gas, and r is the particle radius.

As is shown in the theoretical and experimental studies of [3], the determining parameter of the force of friction of a disperse medium against the duct walls is the axial stress σ_{2*}^{11}. The force of friction of the powder layer against the walls of a cylindrical duct normalized to a unit volume is expressed as a linear function of the effective stress of the disperse phase:

$$\Theta(\sigma_{2*}^{11}) = 2\theta(\sigma_{2*}^{11})/R = -\mathrm{sign}\,(v_2)c_\theta\sigma_{2*}^{11} \qquad (c_\theta = 2A/R).$$

Here R is the duct radius and A is a constant.

Formulation of the Problem. At the initial time $t = 0$, the high-pressure heated gas is in the region $0 \leqslant x < x_1$ of a semiinfinite duct (Fig. 1). The gas is separated by a diaphragm from the powder medium located in the region $x_1 \leqslant x < x_2$. The remaining space is occupied by an unperturbed low-pressure gas. Removal of the diaphragm initiates joint motion of the gas and the powder particles, which is to be calculated.

The boundary conditions of the problem are the nonpenetration condition on the left boundary ($x = 0$) and the initial conditions at infinity.

A solution of the problem is obtained by the modified large-particle method of [9] as applied to two-velocity, two-temperature flows. Pseudoviscous pressures similar to those in [10] were introduced for both phases to suppress oscillations of the solution in zones of high gradients or low (zero) velocities. The calculation accuracy was checked by recalculating with decreased steps in time and space and by comparing with the well-known results [1].

The problem was solved for the following initial parameters: $p_h = 85$ MPa, $p_a = 0.1$ MPa, $T_{ih} = 5447$ K, $T_{ia} = 293$ K, $v_{ih} = v_{ia} = 0$, $\alpha_{10} = \alpha_{1p} = 0.23$ $(x_1 \leqslant x < x_2)$, $\gamma_1 = 1.4$, $\mu_1 = 1.85 \cdot 10^{-5}$ Pa·sec,

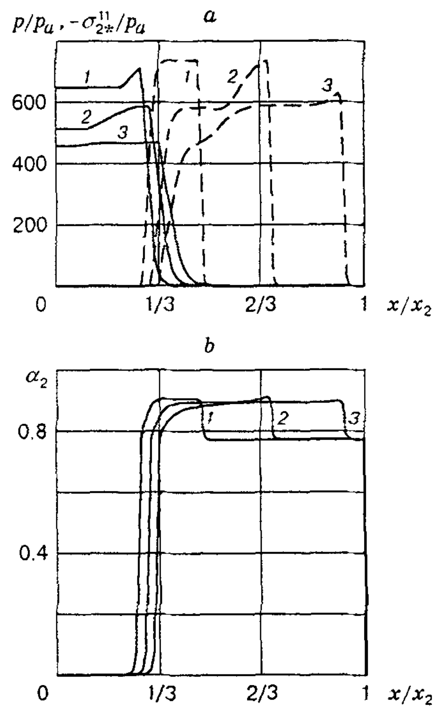

Fig. 2

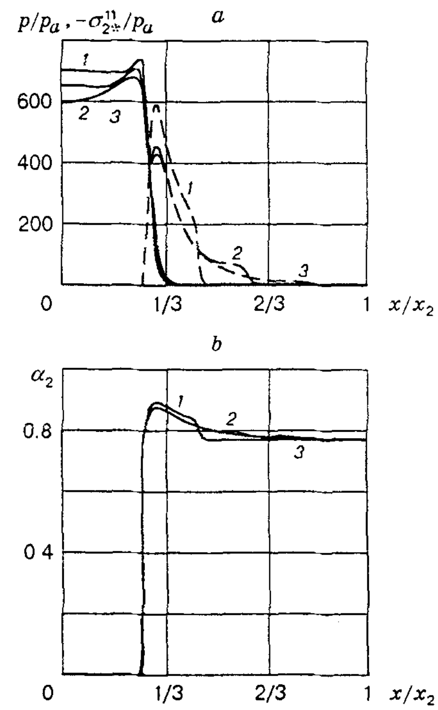

Fig. 3

$\lambda_1 = 0.025$ W/(m · K), $c_v = 716$ m^2/(sec^2· K), $R_1 = 287$ J/(kg · K), $\rho_2^0 = 1300$ kg/m^3, $c_2 = 1066$ m^2/(sec^2· K), $r = 300$ μm, $a_{20} = a_{2p} = 420$ m/sec, $\xi_{2T} = 0$, $x_1 = 0.07$ m, and $x_2 = 0.3$ m. The subscripts h and p refer to the parameters in high and low-pressure regions, and R_1 is the gas constant.

Some Results. To study the effect of friction forces on the process of ejection of the powder medium, we calculated the problem formulated above for the case of interaction between the disperse particles and the duct walls with no friction. Results from calculations of the pulsed motion of the gas and the disperse phases for $c_\theta = 0$ and 50 m^{-1} are given in Figs. 2 and 3, respectively. The solid curves 1–3 show pressure profiles (Figs. 2a and 3a) and volumetric concentration profiles for the powder (Figs. 2b and 3b), and the dashed curves 1–3 correspond to the effective stresses in the disperse phase for times 0.1, 0.2, and 0.3 msec.

Comparison of the results shows that the presence of friction leads to attenuation of the shock wave propagating along the "frame" of the powder. In addition, two qualitatively different regimes of motion of the gas-disperse medium can occur, depending on the initial intensity of the shock wave and the value of c_θ. A substantially wave regime is typical of the cases of powder ejection with no friction [1] with for small c_θ, where a shock wave of rather large intensity "approaches" the right boundary $x = x_2$ (see Fig. 1). In this case, the initial acceleration of disperse particles takes place in a reflected rarefaction wave (Fig. 4). The solid curves 1 and 2 show the variation in the powder velocity in the cross section $x = x_2$ in time for powder motion with no friction and with $c_\theta = 10$ m^{-1}, respectively.

In the case of intense interaction between the particles and the duct walls ($c_\theta = 50$ m^{-1}), the shock wave is considerably attenuated (the dashed curve 3 in Fig. 3a) and the powder plug, through which the gas from the high-pressure chamber is filtered, is actually locked in the duct for a time (the solid curve 3 in Fig. 4). It can be seen from Fig. 4 that the front edge begins to move with a delay in time (the solid and dashed curves 3) that considerably exceeds the time of arrival the shock wave (the solid and dashed curves 1 and 2) for the cases of low friction. In this regime, interphase interaction plays an important part in the initial acceleration of the powder, and this is supported by calculation results for dispersed particle of different radius ($r = 100$ μm). In Fig. 4, these results are shown by curves 1–3 for friction factors $c_\theta = 0$, 10,

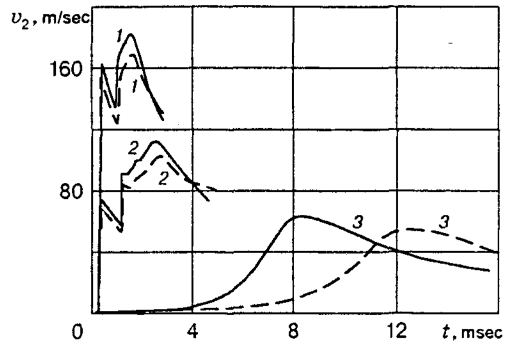

Fig. 4

and 50 m^{-1}, respectively. Under the same initial conditions, an increase in the friction factor gives rise to the self-similarity effect of the powder velocity at the exit cross section ($x = x_2$) with respect to friction. In other words, a significant change in the friction factor leads to an insignificant change in the dispersed-particle velocity.

Thus, the process of powder ejection is studied numerically using the proposed mathematical model of plane, one-dimensional joint motion of the gas and disperse phases taking into account the friction of the latter against the duct walls. It is established that two qualitatively different regimes of motion can occur, depending on the initial conditions in the high-pressure chamber and the friction factor. The effect of self-similarity of the powder exit velocity with respect to friction was established.

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