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PROPAGATION OF SHOCK WAVES IN POLYDISPERSE GAS SUSPENSIONS

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UDC 532.529:518.5

Actual gas suspensions are always polydisperse, i.e., they contain particles of different sizes. The presence of only one or a few particle fractions, each of which contains particles of the same size, is presumed for the description of particle motion in most of the presently known models of gas suspensions [1-4]. The drawback of such a description is that the actual continuous size distribution of the particles is ignored. The equations of motion of polydisperse gas suspensions with a continuous particle size distribution function have been considered in a linear (acoustic) approximation in [5, 6]. It was shown in [6] that the motion of a polydisperse gas suspension cannot be described completely, in general, using a model of a monodisperse gas suspension. The problem of describing the motion of a polydisperse gas suspension with a continuous particle size distribution function behind nonlinear (shock) waves arises in this connection.

In the present paper we obtain a system of integrodifferential equations of motion of an inert, polydisperse gas suspension with a continuous particle size distribution function with allowance for collisions between particles of different sizes. On the basis of the equations derived and the method developed for their numerical solution, we calculate the structure and damping of shocks in polydisperse gas suspensions. We establish the satisfactory agreement between the calculated data and the results of [7, 8]. We show that the structure of shocks in polydisperse gas suspensions depends to a considerable extent on the disperse composition of the ensemble of particles.

1. Basic Equations. By analogy with [5, 6], a polydisperse gas suspension is assumed to consist of a collection of an infinite number of monodisperse fractions of spherical incompressible particles, the radius of which is in the interval from a to a + da. The number of particles in one such fraction per unit volume is

$$d\tilde{n} = \tilde{N}(a,\ x,\ t)\,da,$$

where x is the spatial coordinate of the particles; t is time; $\tilde{N}$ is the size distribution function of the particles. The total number of particles of all sizes per unit volume of the mixture is

$$n = \int\limits_{a_{\min}}^{a_{\max}} \tilde{N}(a,\ x,\ t)\,da$$

Tyumen'. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 2, pp. 24-31, March-April, 1993. Original article submitted July 23, 1991; revision submitted January 29, 1992.

(a_{min} and a_{max} are the minimum and maximum particle sizes). The quantity $d\tilde{n}$ is assumed to be large enough that the motion of a particle fraction can be described by the methods of the mechanics of multiphase continuous media [1].

We also make the following assumptions: in the initial state, the polydisperse gas suspension is homogeneous [$\tilde{N}(a, x, 0) = \tilde{N}_0(a)$, $n(x, 0) = n_0 = \text{const}$]; there is no mass transfer between phases or fragmentation and agglomeration of particles; collisions between particles of different sizes are absolutely elastic; there are no external mass forces; the contributions of unsteady Archimedes forces, the associated mass, and the Busse force to the total force of the interaction between the phases of gas and particles are negligible. The latter assumption is valid if the particle content by volume in the mixture is sufficiently small (much less than unity) [9].

We illustrate the derivation of the equations of motion of a polydisperse gas suspension with a continuous particle size distribution function using the example of the equation of conservation of mass for the suspension, which for a monodisperse particle fraction (with radii in the range from a to a + da) has the form

$$\frac{\partial(d\tilde{\rho}_2)}{\partial t}+\frac{\partial(d\tilde{\rho}_2)\tilde{v}_2}{\partial x}=0 \quad (d\tilde{\rho}_2=\tilde{m}_2 d\tilde{n}=\tilde{m}_2\tilde{N}da), \tag{1.1}$$

where $d\tilde{\rho}_2$ is the mean particle density of the monodisperse fraction; and $\tilde{m}_2$ and $\tilde{v}_2$ are the mass and velocity of particles of radius a. After dividing the left and right sides of Eq. (1.1) by $\tilde{m}_2 da$, we get the equation of conservation of numbers of particles, which in the absence of phase transitions is equivalent to the equation of conservation of mass for the suspension:

$$\frac{\partial\tilde{N}}{\partial t}+\frac{\partial\tilde{N}\tilde{v}_2}{\partial x}=0. \tag{1.2}$$

Reasoning similarly, we obtain the system of equations of motion of a polydisperse gas suspension, generalizing the corresponding system of equations for a multifraction gas suspension [1] to the case of a continuous particle size distribution:

$$\tilde{m}_2\left(\frac{\partial\tilde{N}\tilde{v}_2}{\partial t}+\frac{\partial\tilde{N}\tilde{v}_2^2}{\partial x}\right)=\tilde{N}(\tilde{f}_\mu+\tilde{f}_c); \tag{1.3}$$

$$\tilde{m}_2\left(\frac{\partial\tilde{N}\tilde{e}_2}{\partial t}+\frac{\partial\tilde{N}\tilde{e}_2\tilde{v}_2}{\partial x}\right)=\tilde{N}\tilde{q}_{12}; \tag{1.4}$$

$$\frac{\partial\rho_1}{\partial t}+\frac{\partial\rho_1 v_1}{\partial x}=0; \tag{1.5}$$

$$\frac{\partial\rho_1 v_1}{\partial t}+\frac{\partial\rho_1 v_1^2}{\partial x}+\frac{\partial p}{\partial x}=-F_{12}; \tag{1.6}$$

$$\begin{gathered}\frac{\partial}{\partial t}(\rho_1 v_1+E_\rho)+\frac{\partial}{\partial x}(\rho_1 E_1 v_1+E_{\rho v})+\frac{\partial}{\partial x}(p\alpha_1 v_1+p\alpha_v)=0,\\ \rho_1=\rho_1^0\alpha_1,\ \alpha_1+\alpha_2=1,\ E_1=e_1+0{,}5v_1^2,\\ \alpha_2=\int_\Delta\frac{\tilde{m}_2}{\rho_2^0}\tilde{N}da,\ \tilde{m}_2=\frac{4}{3}\pi\rho_2^0 a^3,\\ \tilde{E}_2=\tilde{e}_2+0{,}5\tilde{v}_2^2,\ E_\rho=\int_\Delta\tilde{m}_2\tilde{E}_2\tilde{N}da,\\ E_{\rho v}=\int_\Delta\tilde{m}_2\tilde{E}_2\tilde{v}_2\tilde{N}da,\ \alpha_v=\int_\Delta\frac{\tilde{m}_2}{\rho_2^0}\tilde{N}\tilde{v}_2 da,\ F_{12}=\int_\Delta\tilde{f}_\mu\tilde{N}da.\end{gathered} \tag{1.7}$$

Equations (1.2)-(1.4) are the laws of conservation of particle mass and momentum, as well as the equation of heat influx to the disperse particles of radius a; (1.5) and (1.6) are the laws of conservations of gas mass and momentum; (1.7) is the law of conservation of the total energy of the mixture. Here the subscripts 1 and 2 pertain to parameters of the gas and particles, respectively; quantities that depend on particle radius a are marked by a tilde ~; the symbol Δ below the integral sign shows integration over particle sizes from a_{min} to a_{max}; ρ_i, ρ_i^0, α_i, v_i, e_i, and E_i are the average and true density, content by volume, mass velocity, specific internal energy, and total energy of the i-th phase (i = 1, 2); $\tilde{e}_2$ and $\tilde{E}_2$ are the specific internal energy and total energy of particles of radius a; E_ρ is the total energy of all particles per unit volume of the mixture; $E_{\rho v}$ is the total energy flux of the ensemble of particles through a unit surface per unit time; α_v, is the average-mass velocity of the disperse particles; p is the gas pressure; $\tilde{f}_\mu$ is the interphase frictional force between single particles of radius a and the gas; $\tilde{f}_c$ is the force of collisions between a single particle of radius a and particles of other sizes; F_{12} is the interphase frictional force exerted by the gas on the ensemble of particles of different sizes per unit volume of the mixture; $\tilde{q}_{12}$ is the intensity of the thermal interaction between the gas and particles of radius a.

We close the system of integrodifferential equations (1.2)-(1.7) by specifying the equations of state of the phases and the laws of interaction between phases and interaction between colliding particles of different sizes. For the equations of state of the phases we take the equations of an ideal, calorically perfect gas and of incompressible solid particles:

$$p = \rho_1^0 R_1 T_1,\ e_1 = c_1 T_1\ \ (R_1 = (\gamma - 1) c_1 \equiv \text{const}),\ \rho_2^0 = \text{const},\ \tilde{e}_2 = c_2 \tilde{T}_2 \quad (c_2 = \text{const}). \tag{1.8}$$

Here R_1 is the gas constant; c_i are the specific heats of the gas (i = 1) and the particles (i = 2) at constant volume; γ is the adiabatic index of the gas; T_1 is the gas temperature; and $\tilde{T}_2$ is the temperature of the fraction of particles of radius a.

The interphase frictional force $\tilde{f}_\mu$ and the intensity of contact heat transfer $\tilde{q}_{12}$ between an individual particle of radius a and the gaseous phase are specified by the equations [1]

$$\begin{gathered}\tilde{f}_\mu = 0{,}5\pi a^2 \tilde{C}_d \rho_1^0 |v_1 - \tilde{v}_2| (v_1 - \tilde{v}_2),\\ \tilde{C}_d = \frac{24}{\widetilde{\mathrm{Re}}_{12}} + \frac{4}{\sqrt{\widetilde{\mathrm{Re}}_{12}}} + 0{,}4,\ \ \widetilde{\mathrm{Re}}_{12} = \frac{2a\rho_1^0 |v_1 - \tilde{v}_2|}{\mu_1},\ \ \tilde{q}_{12} = 2\pi a \widetilde{\mathrm{Nu}}_{12} \lambda_1 (T_1 - \tilde{T}_2),\\ \widetilde{\mathrm{Nu}}_{12} = 2 + 0{,}6 \widetilde{\mathrm{Re}}_{12}^{0,5} \mathrm{Pr}_1^{0,33},\ \ \mathrm{Pr}_1 = \gamma c_1 \mu_1/\lambda_1 \quad (\lambda_1,\ \mu_1 = \text{const}),\end{gathered} \tag{1.9}$$

where $\tilde{C}_d$ is the aerodynamic drag coefficient for a solid spherical particle; $\widetilde{\mathrm{Nu}}_{12}$, Pr_1, and $\widetilde{\mathrm{Re}}_{12}$ are the Nusselt, Prandtl, and Reynolds numbers; and μ_1 and λ_1 are the dynamic viscosity and thermal conductivity of the gas.

The equation for the force $\tilde{f}_c$ of collisions between particles of different sizes is obtained by calculating the number of collisions between particles of radius a and particles of radius a_1 per unit volume of space and per unit time. We then multiply that number of collisions by the change in the momentum of a particle of radius a in one elastic collision, and then sum over all sizes a_1:

$$\begin{gathered}\tilde{f}_c = \frac{8\pi^2}{3} \varkappa^{(F)} \rho_2^0 \int_\Delta f(a, a_1) |\tilde{w}| \tilde{w} \tilde{N}(a_1, x, t)\, da_1,\\ f(a, a_1) = (a_1 a)^3 (a_1 + a)^2 (a_1^3 + a^3)^{-1},\\ \tilde{w} = \tilde{v}_2(a, x, t) - \tilde{v}_2(a_1, x, t) \qquad (a_{\min} \leqslant a_1 \leqslant a_{\max})\end{gathered} \tag{1.10}$$

($\varkappa^{(F)}$ is a coefficient characterizing the fraction of the momentum transferred, on the average, from a particle of radius a to a particle of radius a_1 in one collision between them). According to the experimental data of [10], for relative collision velocities ~10 m/sec, we have $\varkappa^{(F)} \simeq 0.1$.

2. Statement of the Problem. We consider the following problem, which applies to the conditions of the experiments described in [7, 8], in which the laws of propagation of shocks in inert gas suspensions were studied with shock tubes.

We have a straight shock tube of length L, consisting of a high-pressure and a low-pressure chamber (HPC and LPC, respectively), separated by a diaphragm. At the initial time t = 0, the HPC $(0 \leqslant x \leqslant x_*)$ is filled with compressed gas, and the LPC is partially $(x_* < x < x_{**})$ filled with undisturbed gas and partially $(x_{**} \leqslant x \leqslant L)$ with a polydisperse mixture of inert, solid spherical particles. Our aim is to describe the evolution of the shock, originating in the LPC after the rupture of the diaphragm (decay of the initial discontinuity), that passes through the gas suspension at t > 0.

The initial conditions for the formulated problem are

$$\begin{gathered}p(x, 0) = p_*,\ \ \rho_1^0(x, 0) = \rho_{1*}^0,\ \ T_1(x, 0) = T_0,\\ v_1(x, 0) = 0,\ \ \alpha_1(x, 0) = 1,\ \ \alpha_2(x, 0) = 0\ \ (0 \leqslant x \leqslant x_*),\end{gathered}$$

$$p(x,0)=p_0,\ \rho_1^0(x,0)=\rho_{10}^0,\ T_1(x,0)=T_0,$$
$$v_1(x,0)=0,\ \alpha_1(x,0)=1,\ \alpha_2(x,0)=0\ (x_*<x<x_{**}),$$
$$p(x,0)=p_0,\ \rho_1^0(x,0)=\rho_{10}^0,\ T_1(x,0)=T_0, \tag{2.1}$$
$$v_1(x,0)=0,\ \alpha_1(x,0)=\alpha_{10},\ \alpha_2(x,0)=\alpha_{20}=1-\alpha_{10},$$
$$\tilde{v}_2(a,x,0)=0,\ \tilde{T}_2(a,x,0)=T_0,\ \tilde{N}(a,x,0)=\tilde{N}_0(a)\ (x_{**}\leqslant x\leqslant L).$$

For the boundary condition at the left end of the shock tube (x = 0), we take the condition of equality of the velocity of the gaseous phase to zero:

$$v_1(0,t)=0. \tag{2.2}$$

We did not set up a boundary condition for the disperse phase at x = 0 because of the absence of particles in the vicinity of the left-hand wall of the tube during the entire time of the investigated motion. At the right-hand end of the shock tube (x = L) we set up the condition of nonpenetration for the gas and free penetration for the particles:

$$v_1(L,t)=0,\ \tilde{v}_2(a,L_+,t)=\tilde{v}_2(a,L_-,t). \tag{2.3}$$

The system of integrodifferential equations (1.1)-(1.10) with initial conditions (2.1) and boundary conditions (2.2) and (2.3) was solved numerically by the large-particle method [11] using the algorithm of [12]. The integral quantities E_ρ, $E_{\rho v}$, α_v, α_2, and F_{12} were calculated from Simpson's formula. The calculation program was written in the algorithmic language Fortran-77. The calculations were run on a Vesta-88 microcomputer. The typical time of calculation of one version of the motion of a gas suspension with five to ten particle fractions was ~5 h. The calculation accuracy was monitored by a recalculation with reduced step sizes in time and space.

All of the calculations were carried out using the following values of the thermodynamic parameters of the gaseous and disperse phases, corresponding to the experiments of [7, 8]: the gas was air [7, 8]: T_0 = 293 K, p_0 = 0.1 MPa, ρ_{10}^0 = 1.29 kg/m³, γ = 1.4, $a_{10} = (\gamma p_0/\rho_{10}^0)^{0.5}$ = 341 m/sec, c_1 = 716 m²/(sec²·deg), $\mu_1 = 1.85\cdot10^{-5}$ kg(m·sec), $\lambda_1 = 2.6\cdot10^{-2}$ kg·m/(sec³·deg); particles of quartz sand [7]: ρ_2^0 = 2650 kg/m³, c_2 = 754 m²/(sec²·deg); glass particles [8]: ρ_2^0 = 2500 kg/m³, c_2 = 766 m²/(sec²·deg).

In the first series of calculations, as in the experiments of [7], the length L of the shock tube was 7.1 m, and the lengths of the HPC (x_*) and the LPC ($L - x_*$) were 1.8 m and 5.3 m. The length of the region of undisturbed gas in the LPC was 2 m (x_{**} = 3.8 m) and the length of the layer of gas suspension was 3.3 m.

In the second series of calculations, corresponding to the experiments of [8], the lengths of the shock tube and of its HPC and LPC were 7.81, 2, and 5.81 m. The length of the region of undisturbed gas in the LPC was 1.05 m and the length of the layer of gas suspension was 4.76 m.

There are no data on the particle size distribution function $\tilde{N}_0(a)$ in [7], unfortunately. Only the range of variation of the particle radii is given: a_{min} = 1.5 μm and a_{max} = 4.5 μm. In this connection, we chose a unimodal gamma distribution for the calculations:

$$\tilde{N}_0(a)=Aa\exp\left[-\frac{1}{2}\left(\frac{a}{a_*}\right)^2\right]\quad (a_*=\text{const}). \tag{2.4}$$

The constant A was determined from the normalization condition

$$\alpha_{20}=\int_\Delta \frac{\tilde{m}_2}{\rho_2^0}\tilde{N}_0(a)\,da.$$

For the chosen particle size distribution function (2.4), we have

$$A=\frac{3\alpha_{20}}{8\sqrt{2}\,\pi a_*^5}\left\{\left[-z(z^2+1{,}5)\exp(-z^2)+0{,}75\sqrt{\pi}\,\mathrm{erf}(z)\right]\Big|_{z_{min}}^{z_{max}}\right\}^{-1}$$
$$\left(z=\frac{a}{\sqrt{2}\,a_*},\quad a_{min}\leqslant a_*\leqslant a_{max}\right).$$

The constant a_* was specified to be 2 μm.

More detailed information about the spectrum of the polydiserse gas suspension is given in [8]. The range of variation of particle radii (a_{min} = 2.5 μm, a_{max} = 32.5 μm) is given,

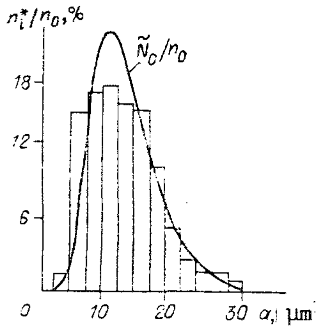

Fig. 1

and the histogram of the fractional composition of the gas suspension, shown in Fig. 1, was determined experimentally.

In the present paper we propose to approximate the experimental histogram of [8] by the normal logarithmic law

$$\tilde{N}_0'(a) = \frac{n_0}{a \ln\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln a - M}{\ln\sigma}\right)^2\right] \quad (M = \ln a_M). \tag{2.5}$$

Here a_M is the so-called median particle radius [13]; M is the mathematical expectation (mean value) of the discrete quantity $\ln a_j$ ($j = 1, 2, \ldots, J$); σ is the standard (rms) deviation of the logarithms of particle radii from the mean; $\ln^2\sigma$ is the variance of the discrete quantity $\ln a_j$ ($j = 1, 2, \ldots, J$). The corresponding equations for finding M and $\ln^2\sigma$ from the experimental histograms are [14]

$$M = \sum_{j=1}^{J} \ln a_j \frac{n_j^*}{n_0}, \quad \ln^2\sigma = \sum_{j=1}^{J} (\ln a_j - M)^2 \frac{n_j^*}{n_0},$$

where n_j^* and a_j are the number density and radius of particles of the j-th fraction.

The distribution function (2.5) satisfies the normalization

$$\int_0^\infty \tilde{N}_0'(a)\, da = n_0.$$

Because the range of particle radii is actually finite, instead of the function $\tilde{N}_0'(a)$ we used the function $\tilde{N}_0(a) = k\tilde{N}_0'(a)$, which satisfies the normalization over a finite range of variation of particle radius ($\Delta = a_{min} \to a_{max}$):

$$\int_\Delta \tilde{N}_0(a)\, da = n_0.$$

For all of the experimental data of [8] considered below, k = 1.214, M = 0.393, and $\ln^2\sigma$ = 2.869.

Let us turn to the results of numerical modeling of the propagation of shocks in polydisperse inert gas suspensions as applied to the experimental conditions of [7, 8].

3. Some Results. In Fig. 2 we show calculated (dashed curves) and experimental (solid curves [7]) oscillograms of the pressure behind shocks passing through polydisperse gas suspensions: a) shock with a discontinuity; b) shock with a completely diffuse structure and no discontinuity. The initial relative mass content of the suspension in the LPC of the shock tube is ρ_{20}/ρ_{10} = 1 and 1.7 for a and b, and the ratio of initial pressures in the HPC and

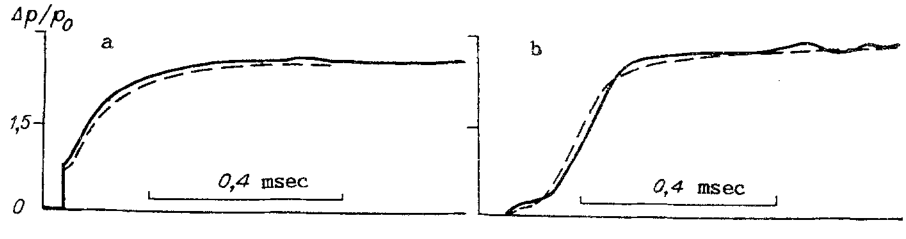

Fig. 2

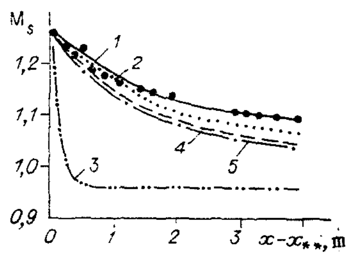

Fig. 3

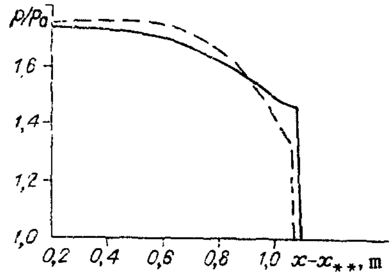

Fig. 4

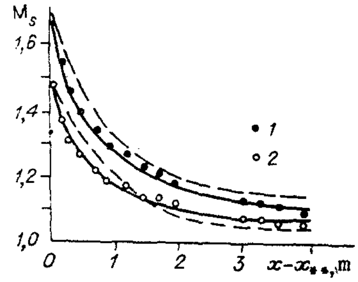

Fig. 5

LPC is p_*/p_0 = 11.65 and 11.06 for a and b. The pressure oscillograms correspond to sensors mounted in the LPC of the shock tube at a distance x = 4.8 m from its left end. A comparison of the calculated and experimental data (Fig. 2) indicates their satisfactory agreement. The maximum relative error in the theory in the zone of quasi-equilibrium motion of the phases does not exceed 4.5%.

In Fig. 3 we compare calculated and experimental [8] Mach numbers $M_S = D/a_{10}$ at the front of a stepped shock propagating through a gas suspension (ρ_{20}/ρ_{10} = 0.63) as a function of the distance it has traveled in the mixture. Experimental values are marked by dots, curve 1 is the numerical solution obtained using the system of equations (1.1)-(1.10) with a normal-logarithmic particle size distribution function, 2 and 3 are numerical solutions corresponding to models of a monodisperse gas suspension with a_{max} = 32.5 μm and a_{min} = 2.5 μm, respectively, 4 is the numerical solution [8] found from the model of a monodisperse gas suspension (a_0 = 13.5 μm), and 5 is the numerical solution of the authors of the present paper corresponding to the model of a monodisperse gas suspension with an effective particle radius a_* = 17.5 μm, determined from the acoustic theory of a gas suspension for brief disturbances [6]:

$$a_* = \left[\int_\Delta \widetilde{N}_0(a)\, a^3 da \Big/ \int_\Delta \widetilde{N}_0(a)\, a da\right]^{1/2}. \tag{3.1}$$

The Mach number of the shock incident on the gas suspension is M_0 = 1.258, which corresponds to a ratio of initial pressures in the HPC and LPC of the shock tube p_*/p_0 = 12.0.

As seen from Fig. 3, calculations using the model of a polydispserse gas suspension are in satisfactory agreement (within 6%) with experimental data. Calculations based on the model of a monodisperse mixture of gas and particles do not describe properly the damping of the leading shock discontinuity. It must be noted that the inadequate description of experimental results based on the model of a monodisperse gas suspension with the effective particle radius (3.1) indicates the significant contribution of nonlinear effects to the evolution of the leading shock discontinuity.

The qualitative influence of polydisperseness on the structure of an unsteady shock passing through a gas suspension is illustrated in Fig. 4, in which we show calculated pressure profiles at t = 2.835 msec (time is reckoned from the time of interaction of the wave with the cloud of particles). The parameters of the mixture and the other initial conditions are the same as in Fig. 3. The solid curve is the solution corresponding to the model of a polydisperse gas suspension and the dashed curve is the solution corresponding to the model of a monodisperse mixture with an effective particle radius 17.5 μm [6].

As seen from Fig. 4, the fractional composition of the suspension of disperse particles significantly affects the evolution of a passing shock: less intense damping of the shock discontinuity is observed in a polydisperse gas suspension, so that a longer zone of equalization of the velocities and temperatures of the phases is formed than in a monodisperse mixture of gas and particles. The latter indicates that in a polydisperse gas suspension, the interphase frictional force exerted by the gas on the ensemble of particles is less than the analogous force for a monodisperse mixture (interphase heat transfer plays a lesser role than interphase friction).

In Fig. 5 we compare calculated and experimental [8] Mach numbers of a shock passing through a gas suspension as a function of distance traveled. Points 1 and 2 are experimental values corresponding to M_0 = 1.7 (p_*/p_0 = 22.0) and 1.48 (p_*/p_0 = 17.5) and ρ_{20}/ρ_{10} = 1.4 and 1.25, the solid curves are the numerical solution obtained using the above model of a polydisperse gas suspension and the same data (distribution function and spectrum) as in Figs. 1, 3, and 4, and the dashed curves are the numerical solution [8] based on the model of a monodisperse mixture with an effective particle radius 13.5 μm. A comparison of these calculated and experimental functions indicates that the experimental data are described best (within 6%) by numerical solutions based on the model of a polydisperse gas suspension.

The suggested method of writing and solving a system of integrodifferential equations can thus be used to calculate unsteady one-dimensional flows of inert polydisperse gas suspensions with a continuous particle size distribution function. Our calculations showed that the experimental results can be described best by a model of a polydisperse mixture of gas and particles. The structure and damping of a shock in a polydisperse gas suspension depend to a considerable extent on the disperse composition of the mixture. The effect of the collision of particles of different sizes behind $1 \lesssim M_0 \lesssim 2$ shocks in mixtures with $0 < \rho_{20}/\rho_{10} \lesssim 2$ and $1.5 \lesssim a \lesssim 33$ μm is negligible.

The authors wish to thank O. N. Pichugin for assistance in compiling the computer program.

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