Journal of Applied Mechanics and Technical Physics, Vol. 40, No. 1, 1999

BEHAVIOR OF THE UNSTEADY JET OF A MIXTURE OF A PRESSURIZED GAS AND DISPERSED PARTICLES DISCHARGED FROM A CIRCULAR DUCT INTO THE ATMOSPHERE

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UDC 532.529.5

The unsteady axisymmetric jet produced by discharge of a mixture of a pressurized gas and dispersed particles from a circular duct into the atmosphere is studied within the framework of two-velocity, two-temperature gas dynamics. An attempt is undertaken to allow for the effective pressure due to random particle motion. The collision mechanism is found to be essential to radial expansion of the flow. Experimental data that support the results obtained are reported.

Introduction. Development of new technologies for fire extinguishing, neutralization of toxic vapors and fluids, and protective shielding is based on pulsed ejection and spraying of disperse working media. In this connection, it is desired to establish the regularities of the two-dimensional, axisymmetric, two-phase jet formed upon discharge of a pressurized gas with dispersed particles from a circular duct of finite dimensions into the atmosphere.

The present paper continues our studies [1], in which ducted flows were treated within the model of a collision-free, two-phase, gas-disperse medium. A feature of gas-dispersion flow in the out-of-duct region is that the collision mechanism plays an important part in random particle motion. This is manifested primarily in radial expansion of the two-phase jet and is supported by the experimental data reported below and results of comparative calculations using the collision-free model and considering the effective pressure of the disperse phase.

1. Formulation of the Problem. We consider a two-phase disperse mixture of particles and a carrier phase (gas). To simplify the mathematical description of the mixture, we adopt the following assumptions [2]: the particle sizes are larger than the molecular-kinetic dimensions and smaller than the distances at which the parameters of the mixture change appreciably; the mixture is monodisperse: there are no fragmentation, aggregation or formation of new particles taking place; the gas is calorically perfect, the viscosity and thermal conductivity are manifested only in interphase interaction processes; the energy of the small-scale motion of the carrier gas is low.

From a statistical viewpoint, any disperse phase can be treated as a real gas. Conservation equations for a pseudogas of particles can be derived by the classical Enskog method applied to the Boltzmann equation [3], which corresponds to the Navier–Stokes approximation for a disperse phase. Buevich [3] points to the possibility of simplifying this system of equations of motion by ignoring quasiviscous stresses and pulsation energy flux (an analog of thermal conductivity in a gas). Then, the isotropic pressure of the pseudogas of particles should be taken into account in the equation of conservation of momentum, and the specific energy of particle pulsation motion and the work done by pressure forces to compress or expand the pseudogas should be taken into account in the equation of conservation of the total energy of the mixture.

Mozhaiskii Military Spacecraft Engineering Academy, St. Petersburg 197082. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 40, No. 1, pp. 151–157, January–February, 1999. Original article submitted April 18, 1997.

 0021-8944/99/4001-0130 $22.00

Within the adopted concept, the equations of spatial motion of the gas-disperse mixture with allowance for inertial phenomena in the flow around particles [2] can be written as

$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot \rho_i \mathbf{v}_i = 0,$$

$$\frac{\partial \rho_1 \mathbf{v}_1}{\partial t} + \nabla \cdot \rho_1 \mathbf{v}_1 (\mathbf{v}_1 \cdot \mathbf{l}) + \beta_1 \nabla p + (1-\beta_2)\nabla p_d = -\beta_3 \mathbf{F}_\mu + \beta_3 \rho_1 \mathbf{g} + (1-\beta_2)(\rho_1 + \rho_2)\,\mathbf{g},$$

$$\frac{\partial \rho_2 \mathbf{v}_2}{\partial t} + \nabla \cdot \rho_2 \mathbf{v}_2 (\mathbf{v}_2 \cdot \mathbf{l}) + (1-\beta_1)\nabla p + \beta_2 \nabla p_d = \beta_3 \mathbf{F}_\mu - \beta_3 \rho_1 \mathbf{g} + \beta_2 (\rho_1 + \rho_2)\,\mathbf{g},$$

$$\frac{\partial \rho_2 u_2}{\partial t} + \nabla \cdot \rho_2 u_2 \mathbf{v}_2 = Q, \qquad \frac{\partial \rho_2 k_2}{\partial t} + \nabla \cdot \rho_2 k_2 \mathbf{v}_2 + p_d \nabla \cdot \mathbf{v}_2 = q_+ - q_-, \tag{1.1}$$

$$\frac{\partial}{\partial t}(\rho_1 E_1 + \rho_2 E_2) + \nabla \cdot [\rho_1 E_1 \mathbf{v}_1 + \rho_2 E_2 \mathbf{v}_2 + p(\alpha_1 \mathbf{v}_1 + \alpha_2 \mathbf{v}_2) + p_d \mathbf{v}_2] = \rho_1 \mathbf{g} \cdot \mathbf{v}_1 + \rho_2 \mathbf{g} \cdot \mathbf{v}_2,$$

$$\rho_i = \rho_i^0 \alpha_i \quad (i = 1, 2), \quad E_1 = u_1 + 1/2 v_1^2, \quad E_2 = u_2 + k_2 + 1/2 v_2^2,$$

$$\beta_1 = \frac{\alpha_1 (2 + \chi_m \rho_1^0 / \rho_2^0)}{2 + \chi_m (\alpha_2 + \alpha_1 \rho_1^0 / \rho_2^0)}, \quad \beta_2 = \frac{2 + \chi_m \alpha_2}{2 + \chi_m (\alpha_2 + \alpha_1 \rho_1^0 / \rho_2^0)}, \quad \beta_3 = \frac{2}{2 + \chi_m (\alpha_2 + \alpha_1 \rho_1^0 / \rho_2^0)}.$$

Here and below, the subscripts 1 and 2 refer to the parameters of the carrier and disperse phases, respectively, the superscript 0 refers to the true value of density, ∇ is the Hamiltonian operator $\rho_i \mathbf{v}_i (\mathbf{v}_i \cdot \mathbf{l})$ is the flux of vector momentum of the ith phase through the surface normal to unit vector $\mathbf{l}$, α_i, ρ_i, $\mathbf{v}_i$, E_i, and u_i are the volumetric fraction, normalized density, vector velocity, and total and internal energies of a unit mass of the ith phase, p is the gas pressure, p_d is the effective pressure due to random particle motion, k_2 is the pulsation energy of a unit mass of the disperse phase, $\mathbf{g}$ is the free-fall acceleration vector, $\mathbf{F}_\mu$ and Q are the viscous component of the interphase interaction force and the rate of heat exchange between the gas and the particles, q_+ and q_- are the rates of energy supply and dissipation due to random particle motion in a unit volume of the mixture, χ_m is a coefficient that takes into account the effect of the nonspherical shape and nonsingleness of the particles on the attached-mass forces, ($\chi_m = 1$ for spherical particles), and t is time.

The system of quasilinear equations (1.1) is supplemented by the following equations of state for an ideal, calorically perfect gas and incompressible solid particles:

$$p = (\gamma_1 - 1)\rho_1^0 u_1, \quad u_1 = c_V T_1, \quad u_2 = c_2 T_2, \quad \gamma_1, c_V, c_2, \rho_2^0 \equiv \text{const}. \tag{1.2}$$

Here T_1 and T_2 are the temperatures of the carrier gas and the particles and γ_1, c_V, and c_2 are the adiabatic exponent, the specific heat of the gas with constant volume, and the specific heat of the particles.

The rates of interphase friction and heat transfer are specified by the following relations [2, 4, 5]:

$$\mathbf{F}_\mu = (3/8)(\alpha_2 / r) C_\mu \rho_1 \mathbf{w}_{12} |w_{12}|, \qquad \mathbf{w}_{12} = \mathbf{v}_1 - \mathbf{v}_2,$$

$$C_\mu = \begin{cases} C_\mu^{(1)} = \dfrac{24}{\mathrm{Re}_{12}} + \dfrac{4.4}{\mathrm{Re}_{12}^{0.5}} + 0.42, & \alpha_2 \leqslant 0.08, \\ C_\mu^{(2)} = \dfrac{4}{3\alpha_1}\left(1.75 + \dfrac{150\,\alpha_2}{\alpha_1 \mathrm{Re}_{12}}\right), & \alpha_2 \geqslant 0.45, \\ [(\alpha_2 - 0.08) C_\mu^{(2)} + (0.45 - \alpha_2) C_\mu^{(1)}]/0.37, & 0.08 < \alpha_2 < 0.45, \end{cases} \tag{1.3}$$

$$Q = (3/2)(\alpha_2 / r^2)\lambda_1 \mathrm{Nu}_1 (T_1 - T_2), \quad \mathrm{Nu}_1 = \begin{cases} 2 + 0.106\,\mathrm{Re}_{12} \mathrm{Pr}_1^{1/3}, & \mathrm{Re}_{12} \leqslant 200, \\ 2.27 + 0.6\,\mathrm{Re}_{12}^{0.67} \mathrm{Pr}_1^{1/3}, & \mathrm{Re}_{12} > 200, \end{cases}$$

$$\mathrm{Re}_{12} = 2 r \rho_1^0 w_{12} / \mu_1, \qquad \mathrm{Pr}_1 = c_V \gamma_1 \mu_1 / \lambda_1.$$

Here Re_{12}, Nu_1, and Pr_1 are the Reynolds, Nusselt, and Prandtl numbers, C_μ is the interphase-friction

coefficient, μ_1 is the dynamic viscosity, λ_1 is the thermal conductivity of the gas, and r is the particle radius.

In the Enskog theory of dense gases [3], the equation of state for a pseudogas has the form

$$p_d = (2/3)G(\alpha_2)\rho_2 k_2, \quad G(\alpha_2) = 1/(1-(\alpha_2/\alpha_2^*)^{1/3}), \quad \alpha_2^* = \text{const}, \tag{1.4}$$

where $G(\alpha_2)$ is a correction function that takes into account the increase in the number of collisions in a dense gas compared to a diluted gas.

To complete system (1.1), it is necessary to specify the laws of energy supply q_+ to random particle motion and dissipation of pulsation energy q_- in a unit volume per unit time. The dissipation is caused by inelastic collisions of particles [3] and the viscosity of the surrounding gas. Using linear approximations of relations (1.3), we obtain

$$q_- = \alpha_c k_2^{3/2} + \alpha_\mu k_2, \quad \alpha_c = 4(8\pi/27)^{1/2} k_c (r\rho_2^0)^2 m^{-1} \alpha_2 (G(\alpha_2) - 1),$$

$$\alpha_\mu = \begin{cases} \alpha_\mu^{(1)} = 9\alpha_1\alpha_2\mu_1/r^2, & \alpha_2 \leqslant 0.08, \\ \alpha_\mu^{(2)} = 75\dfrac{\alpha_2^2}{\alpha_1}\dfrac{\mu_1}{r^2}, & \alpha_2 \geqslant 0.45, \\ [\alpha_\mu^{(2)}(\alpha_2 - 0.08) + \alpha_\mu^{(1)}(0.45 - \alpha_2)]/0.37, & 0.08 < \alpha_2 < 0.45, \end{cases}$$

where k_c is a coefficient that describes the mean fraction of the kinetic energy of colliding particles absorbed in a collision and m is the mass of a dispersed particle.

It is known [2] that the annular eddy formed past a sphere in gas flow that is steady at infinity oscillates at approximately $\mathrm{Re} > 130$. As experimental studies [5] showed, during motion of phases relative to one another in a gas-disperse medium, transition from one flow regime to another takes place at about $\mathrm{Re}_{12} = 200$. As the Reynolds number increases, the frequency of the oscillations rises. From the aforesaid, the rate of energy transfer from the relative motion of the phases to random particle motion can be written as

$$q_+ = \begin{cases} nk_+(\mathrm{Re}_{12} - 200)^\omega, & \mathrm{Re}_{12} \geqslant 200, \\ 0, & \mathrm{Re}_{12} < 200. \end{cases}$$

Here k_+ and ω are empirical constants and n is the number of dispersed particles in a unit volume of the mixture.

At the initial moment, the duct contains a stationary mixture of the pressurized gas and the dispersed particles, and outside the duct, there is unperturbed gas with parameters denoted by the subscripts h and a:

$$p = p_h, \quad T_1 = T_2 = T_h, \quad \alpha_1 = \alpha_{1h}, \quad v_1 = v_2 = 0,$$

$$p = p_a, \quad T_1 = T_2 = T_a, \quad \alpha_1 = 1, \quad v_1 = v_2 = 0.$$

Nonpenetration conditions are specified for both phases at the walls and bottom of the duct, and the initial conditions are specified at infinity.

After rupture of the diaphragm that separates the gas-dispersion mixture from the atmosphere, the discharge of the two-phase medium to be calculated begins. The problem was solved for the following initial parameters: $p_h = 0.6$ MPa, $p_a = 0.1$ MPa, $T_{ih} = T_{ia} = 293$ K, $\alpha_{1h} = 0.4$, $\alpha_{1a} = 1$, $\gamma_1 = 1.4$, $\mu_1 = 1.8 \cdot 10^{-5}$ Pa $\cdot$ sec, $\lambda_1 = 0.025$ W/(m $\cdot$ K), $R_1 = 287$ J/(kg $\cdot$ K), $c_V = 716$ m^2/(sec^2 $\cdot$ K), $r = 100$ μm, $\rho_2^0 = 2600$ kg/m^3, $c_2 = 710$ m^2/(sec^2 $\cdot$ K), $k_c = 0$, $k_+ = 5 \cdot 10^{-7}$ W, $\omega = 1$, and $\alpha_2^* = 0.7$, where R_1 is the gas constant. The length and radius of the duct were 0.6 and 0.05 m, respectively.

2. Calculation Procedure. The heterogeneous wave flows studied in this work are characterized by intense interphase interaction. As shown in [6], the method whereby the quantities related to the friction and heat exchange between the gas and the particles are taken into account in the difference scheme can exert a significant influence on the stability and, hence, efficiency of the computational algorithm.

The numerical integration procedure described below is an extension of the algorithm of [6] to the equations of two-velocity, two-temperature, gas-disperse flows with two pressures. For brevity of the derivation, here we describe this procedure for the plane one-dimensional case ignoring gravity.

The initial system (1.1) is split into two stages with respect to the physical processes. In approximation of the resultant system of equations, the force interphase interaction is taken into account at the first stage, and heat transfer at the second. The velocity and total energy of the less inertial carrier phase enter in the source terms implicitly ($\tilde{v}_{1,m}$, $E^{k+1}_{1,m}$), and their analogs for the particles ($v^k_{2,m}$, $E^k_{2,m}$) are allowed for in an explicit manner. Here and below, the tilde denotes the parameters calculated at the first stage, the superscript denotes the time-layer number, the first subscript 1 stands for the gas, 2 for a particle, and the second subscript refers to the mesh number. Since the interphase interaction force (1.3) is a power-law function of $(v_1 - v_2)$, in order to calculate the gas velocity at the first stage explicitly (without iterations), it makes sense to separate the linear part of the expression $\tilde{v}_{1,m} - v^k_{2,m}$ in F_μ.

Stage 1.

$$\tilde{\rho}_1 = \rho^k_{1,m}, \qquad \tilde{\rho}_2 = \rho^k_{2,m}, \qquad \tilde{u}_2 = u^k_{2,m},$$

$$\tilde{v}_{1,m} = \Big[v^k_{1,m}\rho^k_{1,m} - \frac{\tau}{h}\beta^k_{1,m}(p^k_{m+1/2} - p^k_{m-1/2})$$

$$-\frac{\tau}{h}(1-\beta^k_{2,m})(p^k_{d,m+1/2} - p^k_{d,m-1/2}) + \beta^k_{3,m}Av^k_{2,m}\tau\Big]\Big/(\rho^k_{1,m} + \beta^k_{3,m}A\tau),$$

$$\tilde{v}_{2,m} = v^k_{2,m} - \Big[\frac{\tau}{h}(1-\beta^k_{1,m})(p^k_{m+1/2} - p^k_{m-1/2}) + \frac{\tau}{h}\beta^k_{2,m}(p^k_{d,m+1/2} - p^k_{d,m-1/2})$$

$$+\beta^k_{3,m}A(\tilde{v}_{1,m} - v^k_{2,m})\tau\Big]\Big/\rho^k_{2,m},$$

$$\tilde{k}_{2,m} = k^k_{2,m} - p^k_{d,m}\frac{\tau}{h}(v^k_{2,m+1/2} - v^k_{2,m-1/2})\Big/\rho^k_{2,m},$$

$$\tilde{E}_{1,m} = E^k_{1,m} - \frac{\tau}{h}[p^k_{m+1/2}(\alpha^k_{1,m+1/2}v^k_{1,m+1/2} + \alpha^k_{2,m+1/2}v^k_{2,m+1/2})$$

$$-p^k_{m-1/2}(\alpha^k_{1,m-1/2}v^k_{1,m-1/2} + \alpha^k_{2,m-1/2}v^k_{2,m-1/2})]/\rho^k_{1,m},$$

$$\tilde{E}_{2,m} = u^k_{2,m} + \tilde{k}_{2,m} + \tilde{v}^2_{2,m}/2.$$

Stage 2.

$$\rho^{k+1}_{i,m} = \rho^k_{i,m} + (\Delta M_{i,m-1/2} - \Delta M_{i,m+1/2})/h,$$

$$v^{k+1}_{i,m} = [\tilde{v}_{i,m}\rho^k_{i,m} + (\Delta M\tilde{v}_{i,m-1/2} - \Delta M\tilde{v}_{i,m+1/2})/h]/\rho^{k+1}_{i,m},$$

$$u^{k+1}_{2,m} = [\tilde{u}_{2,m}\rho^k_{2,m} + (\Delta M\tilde{u}_{2,m-1/2} - \Delta M\tilde{u}_{2,m+1/2})/h + Q^k_m\tau]/\rho^{k+1}_{2,m},$$

$$k^{k+1}_{2,m} = [\tilde{k}_{2,m}\rho^k_{2,m} + (\Delta M\tilde{k}_{2,m-1/2} - \Delta M\tilde{k}_{2,m+1/2})/h + (q^k_{+,m} - q^k_{-,m})\tau]/\rho^{k+1}_{2,m},$$

$$E^{k+1}_{2,m} = u^{k+1}_{2,m} + k^{k+1}_{2,m} + (v^{k+1}_{2,m})^2/2,$$

$$E^{k+1}_{1,m} = [\tilde{E}_{1,m}\rho^k_{1,m} + \tilde{E}_{2,m}\rho^k_{2,m} - (C + k^{k+1}_{2,m} + (v^{k+1}_{2,m})^2/2)\rho^{k+1}_{2,m}$$

$$+(\Delta M\tilde{E}_{1,m-1/2} + \Delta M\tilde{E}_{2,m-1/2} - \Delta M\tilde{E}_{1,m+1/2} - \Delta M\tilde{E}_{2,m+1/2})]/(\rho^{k+1}_{1,m} + B\tau/c_V),$$

$$A = F^k_{\mu,m}/(v^k_{1,m} - v^k_{2,m}), \qquad B = Q^k_m/(T^k_{1,m} - T^k_{2,m}),$$

$$C = \Big[u^k_{2,m}\rho^k_{2,m} + (\Delta M\tilde{u}_{2,m-1/2} - \Delta M\tilde{u}_{2,m+1/2})/h - B\Big(\frac{(v^k_{1,m})^2}{2c_V} + T^k_{2,m}\Big)\tau\Big]\Big/\rho^{k+1}_{2,m},$$

where τ and h are the mesh steps for time and space, respectively. The pressures of the gas and the pseudogas of particles are determined from the equations of state (1.2) and (1.4). The quantities with fractional subscripts related to the mesh boundaries are equal to half the sum of the corresponding parameters in neighboring meshes, e.g., $p^k_{m+1/2} = (p^k_{m+1} + p^k_m)/2$. The rates of transfer of mass, momentum, and energy through the

mesh boundaries are determined with allowance for the direction of the flow:

$$\Delta M\tilde{\varphi}_{i,m+1/2} = \begin{cases} \rho^k_{i,m}\tilde{\varphi}_{i,m}\tilde{v}_{i,m+1/2}\tau, & \tilde{v}_{m+1/2} \geqslant 0, \\ \rho_{i,m+1}\tilde{\varphi}_{i,m+1}\tilde{v}_{i,m+1/2}\tau, & \tilde{v}_{m+1/2} < 0, \end{cases} \qquad \varphi = \{1, v_1, v_2, E_1, E_2, u_2, k_2\}.$$

To damp oscillations in regions with low (zero) velocity of the carrier phase, it is advantageous to introduce an additional pseudoviscous pressure similar to the one used in [7].

In the general case, the allowable time step of the numerical algorithm depends on a number of factors (initial conditions, rates of interphase friction and heat exchange) [6] and is given by the following condition of the Courant–Friedrichs–Lévy type:

$$\mathrm{Cr} = \frac{\max\limits_m \left(|v^k_{1,m}| + a^k_{1,m}\right)\tau}{h} = \mathrm{const} < 1, \qquad a^k_{1,m} = \left(\frac{\gamma_1 p^k_m}{\rho^{0k}_{1,m}}\right)^{1/2}.$$

Numerical experiments showed that use of the above difference scheme to solve the problem of interest increases the admissible time step severalfold compared to the algorithm of [7].

3. Some Results. As in [1], results of solving the formulated problem are presented in dimensionless form. The phase velocities are normalized to the velocity of sound in the gas-disperse mixture in an equilibrium (for the velocities and temperatures) approximation $a_h = (\gamma p_h/((\rho_{1h} + \rho_{2h})/\alpha_{2h}))^{1/2}$, $\gamma = (c + r_1R_1)/c$, $c = r_1c_{V1} + r_2c_2$, and $r_i = \rho_i/\rho$ $(i = 1, 2)$, the gas pressure to the initial pressure of the unperturbed atmosphere p_a, and the linear dimensions to the duct length L. As the time scale, we use the ratio L/a_h, which is related to the time required for a rarefaction wave to pass from the duct exit to its bottom.

Figures 1–3 show profiles of the axial projections of the gas and particle velocities, the gas pressure, and the volume concentration of the disperse phase (curves 1–4) onto the symmetry axis for various characteristic times and $\mathrm{Sr}^{-1} = a_ht/L = 1.03$, 4.13, and 7.23 (a). The same figures illustrate the atmospheric section of the gas-disperse jet (b).

After decay of the initial discontinuity and dynamic relaxation, a quasicritical two-phase jet flow develops that has the following characteristic structure. A rarefaction wave propagates from the duct exit to its bottom, and the gas-disperse mixture flows in the opposite direction. The axial-velocity components of the two phases differ from one another and attain the highest values at the duct exit (Fig. 1a). Near the exit, there is a region of increased pressure of the gas and the pseudogas of particles, and the velocity vectors of the phases are directed from the symmetry axis, which results in formation of a concentration field of the disperse phase (Fig. 1b). The duration of this stage can be evaluated as the time required for passage of the rarefaction wave from the duct exit to the duct bottom and return of the reflected wave.

For $\mathrm{Sr}^{-1} > (1.5\text{–}2)$, transition from one discharge regime to another takes place. The transition exhibits the following regularities. The maximum of the axial velocity of the disperse phase and then that of the gas are displaced upstream from the duct exit. The gas pressure in the duct falls below the initial pressure of the unperturbed atmosphere, thus causing deceleration of the particles and appearance of a reverse gas flow in the duct (Fig. 2a). The region of increased effective pressure of the pseudogas is displaced downstream. The highest value of the pressure decreases owing to dissipation of the energy of random motion of the dispersed particle. The gas-disperse jet acquires a conical shape with its narrow part at the duct exit (Fig. 2b).

At the final stage ($\mathrm{Sr}^{-1} > 8$), the ducted flow practically ceases (Fig. 3a) and the atmospheric region of the flow has two characteristic parts. In the tail part of the jet, a "leg" forms, with a transverse dimension close to the duct diameter (Fig. 3b). The head part of the jet has a radially diverging oval shape, for which the axial slippage of the phases is significant. Throughout the flow region of the gas-disperse mixture, the gas pressure differs from the initial pressure of the unperturbed atmosphere by not more than 1% and the effective pressure of the pseudogas of particles is low.

Calculations using the collision-free model of [1] were conducted and experiments were performed. A duct in an upright position was filled with quartz sand, separated from the ambient medium with a diaphragm, and pumped up with air. The air pressure in the duct was measured by a calibrated manometer. The unsteady discharge of the gas-disperse mixture was recorded by a "Krasnoyarsk" cine camera. The dimensions of the duct and the parameters of the phases were the same as the initial data given above.

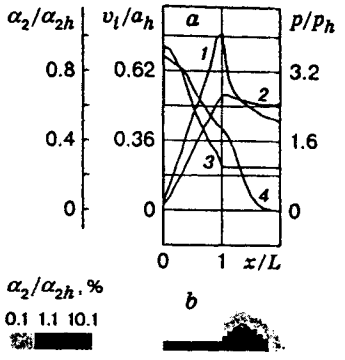

Fig. 1

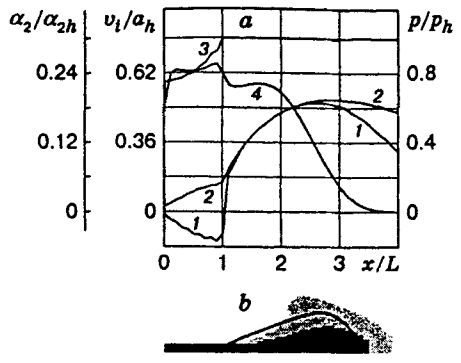

Fig. 2

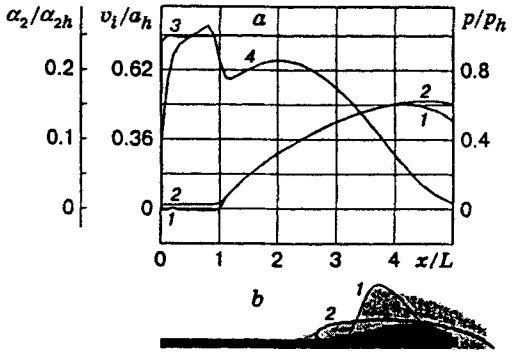

Fig. 3

Results of calculations using the collision-free model are shown in Fig. 3b by curve 2, which corresponds to 0.1% of the initial concentration of the disperse phase. Comparison with the data obtained suggests that the collision mechanism has a significant influence on the radial expansion of the gas-disperse mixture. The visible contour of the jet observed in the experiment is shown by the solid curve in Figs. 1b and 2b and by curve 1 in Fig. 3b. Comparison between the calculated and experimental data indicates that the adopted mathematical model is adequate to the phenomenon studied. Further development of the model requires allowance for the turbulence of the carrier gas.

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