JET FLOW IN A SHALLOW FLUIDIZED BED

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A physical model of a steady jet discharging into a fluidized bed in a vertical direction is examined on the example of plane flow, and the quantities characterizing the exchange of particles and the fluid phase between the jet and the bed are estimated.

The types of jets observed in fluidized beds are very diverse (see the description of experiments in [1, 2], for example), but among them one can distinguish two basic limiting modes. If the bed is deep and the initial velocity of the jet, entering in a vertical direction from below, is low enough, then the tongue of the jet does not reach the free surface of the bed and the jet proves to be unstable, so that a peculiar self-oscillating mode of discharge is realized with separation of the tongue and the formation of a bubble at the end of each cycle [1, 2]. Conversely, if the bed is shallow or the initial velocity of the jet is high, the jet "pierces" the bed and the stable steady mode illustrated in Fig. 1 is realized. With intermediate values of the bed height and discharge velocity certain superpositions of the steady and self-oscillating types of flow are possible, such as the so-called "local spouting mode" [1]. Only steady jets are considered below.

In connection with the fact that a representational model of jet flows is essentially absent we performed a thorough analysis of the known experimental results (particularly those described in [1]) and also set up special experiments on the discharge of steady plane and axisymmetric gas jets into fluidized beds of different heights. The latter made it possible to clarify the physical pattern of the motion, which is required for the construction of its model.

The delivery of an excess of gas through an opening in the gas-distribution grid leads to the formation of a stable jet channel whose cross-sectional area increases monotonically with an increase in distance from the opening. The volume of gas flowing in this channel also increases in comparison with that blown into the bed owing to the injection of some of the gas from the surrounding spaces of the bed, with this "draining" effect of the jet leading to a considerable decrease in the amount of gas moving in the bed in the bubble phase. The penetration of separate particles into the channel occurs in addition, especially noticeable near the grid and gradually weakening with an increase in height above it. These particles are entrained by the ascending gas stream, move in it in a mode of pneumatic transport, and are ultimately carried into the space above the bed (Fig. 1a, b, c).

The abrupt expansion of the jet above the bed leads to a rapid drop in its velocity, which becomes less than the velocity of particle hovering, and to the radial displacement of particles away from the core of the jet. As a result the particles fall onto the upper surface of the bed at different distances from the jet, compensating for the loss of particles at this surface due to the slow descending movement of the disperse phase of the bed in the vicinity of the jet. Such "settling" of the disperse phase leads to the supply of new particles to the surface of the jet channel, which in turn are entrained by the stream and transported by it to the free surface.

The distribution of particles over the lower cross sections of the channel is very uneven and has a minimum at the center of the channel, with the principal mass of particles moving upward in a relatively narrow "boundary layer" adjacent to the walls (this layer has already been taken into account in [3] in an analysis of the gas velocity distribution in the jet). As the height above the grid increases this distribution

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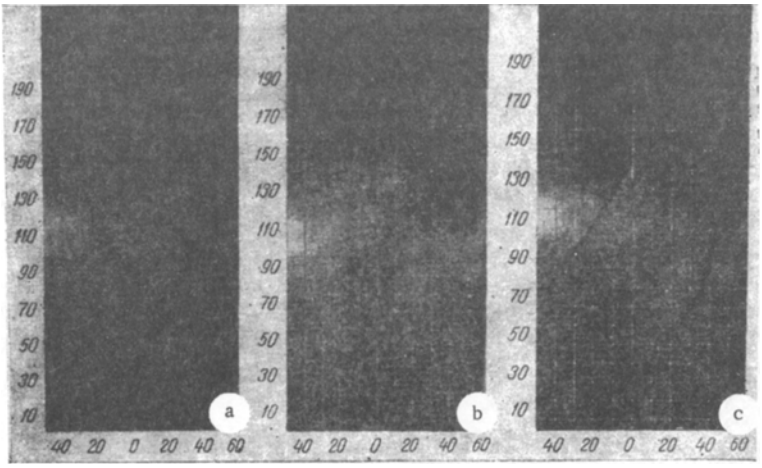

Fig. 1. Typical patterns of steady jets discharging into a fluidized bed. The photographs are arranged in order of decreasing discharge velocity.

levels out, while the average particle concentration in the jet channel increases. If the bed is not too deep and the opening through which the jet discharges is large enough, then the indicated concentration at the exit of the jet from the bed proves to be considerably less than the particle concentration in the compact phase of the bed. With an increase in the height of the bed and a decrease in the size of the opening the concentration of particles in the channel becomes comparable with their concentration in the bed and a local spouting mode sets in (Fig. 1c).

Below we will be confined to an analysis of jets with a low concentration of suspended particles. In this case the pressure drop along the length of the jet channel is considerably less than that over the height of the compact phase of the bed, so that the pressure at the channel boundary can be taken as constant in a first approximation and as coinciding with the pressure at the free surface of the bed. Also neglecting the boundary layer at the channel walls, we arrive at the pattern illustrated schematically in Fig. 2. There is a region D_1, occupied by the compact phase of the bed, and a region D_2, occupied by the rarefied suspension, with the boundary between these regions being formed by the surface AB of the jet channel and the free surface BC. The point B separating these surfaces in Fig. 2 can be determined arbitrarily as the point at which the velocity of the disperse phase normal to the surface is reduced to zero.

Neglecting the inertia of the gas and the shear stresses caused by the molecular viscosity of the gas and the chaotic pulsations of the two phases, we can write the equations of motion in region D_1 in the form

$$-\nabla p-\alpha\mathbf{u}=0,\quad \operatorname{div}(\varepsilon\mathbf{v})=0,\quad \mathbf{u}=\mathbf{v}-\mathbf{w},\quad \rho=1-\varepsilon,$$
$$\rho d_1(\mathbf{w}\nabla)\,\mathbf{w}=-\nabla P+\alpha\mathbf{u}-\rho d_1\mathbf{g},\quad \operatorname{div}(\rho\mathbf{w})=0,\quad \alpha=\alpha(\varepsilon). \tag{1}$$

These equations differ from those obtained rigorously in [4] by the presence of a term containing the pressure P of the disperse phase. The latter is due mainly to the effect of the spreading forces in the bed, which accompany the "rolling" of the particles over one another and are very important for disperse systems which are close to being tightly packed [5, 6]. It is clear that in the general case P represents some function of the porosity and the other parameters. The first equations in (1) describe the filtration of gas in the mobile porous substance formed by the moving particles and they coincide in form with the equations in [7], used to describe jet flows in an immobile granular bed. In a first approximation it is admissible to take the porosity in region D_1 as constant; then P must be considered as some unknown function which is subject to determination from the solution of the problem.

Let us discuss the boundary conditions imposed on the solution of (1). The first group of conditions follows from the requirement of approximate constancy of the pressure at the interface ABC, the condition of nonpenetration of the outer boundary $x = L$, which can consist either of the wall of the apparatus or of the surface of symmetry separating the regions of influence of neighboring jets (see [7]), and from the requirement of constancy of the flow rate of the fluidizing gas through the gas-distribution grid. The mathematical

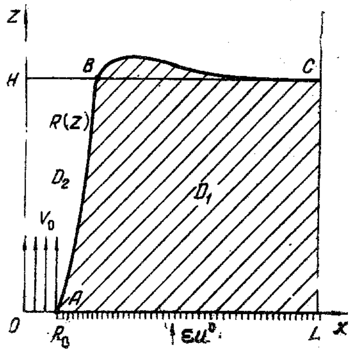

Fig. 2. Sketch explaining the statement of the problem.

representation of these conditions can be formulated in complete analogy with [7]. By introducing the pressure p^0 and the gas velocity u^0 undisturbed by the jet

$$p^0 = \alpha u^0 (H - z) = \rho d_1 g\,(H - z), \quad u_x^0 = 0, \quad u_z^0 = u^0 \tag{2}$$

and the excess pressure $\varphi = p - p^0$, we obtain the problem

$$\Delta\varphi = 0, \quad \mathbf{u} = \mathbf{u}^0 + \mathbf{u}', \quad \mathbf{u}' = -\alpha^{-1}\nabla\varphi, \tag{3}$$

$$\frac{\partial\varphi}{\partial z} = 0 \quad (z = 0); \quad \frac{\partial\varphi}{\partial x} = 0 \quad (x = L); \quad \varphi = -\alpha u^0 (H - z) \quad (r \in ABC),$$

the solution of which allows one, in principle, to find the fields of pressure and relative gas velocity in the spaces between particles in the presence of a jet.

The velocity and pressure of the disperse phase must be determined from the solution of the supplementary boundary-value problem, which follows from (1). The boundary conditions for this problem are obtained from the requirements of continuity of the normal components of the fluxes of particle mass and momentum at the boundary ABC, which represents the free boundary with respect to the disperse phase, and the reduction to zero of the normal component of the particle velocity at the gas-distribution grid and at the outer flow boundary $x = L$. We have

$$\begin{gathered} \rho d_1 (\mathbf{w}\nabla)\,\mathbf{w} = -\nabla P + \alpha \mathbf{u} - \rho d_1 \mathbf{g}, \quad \operatorname{div}\mathbf{w} = 0, \\ w_x = 0 \ (x = L); \quad w_z = 0 \ (z = 0); \quad P = 0 \ (\mathbf{r} \in AB), \\ \rho w_n = Q_s(\mathbf{r}), \quad -P + \rho d_1 w_n^2 = d_1 \Pi_s(\mathbf{r}) \ (\mathbf{r} \in BC). \end{gathered} \tag{4}$$

Here w_n is the normal component of the velocity, while $Q_s(\mathbf{r})$ and $d_1\Pi_s(\mathbf{r})$ are the normal volume and momentum flux densities of the particles arriving at the surface BC from the space above the bed.

The problems (3) and (4) can be considered as independent if the unknown boundary ABC is roughly approximated by some known surface.* In the solution of (3) it is natural to neglect the departures of BC from the horizontal plane $z = H$ and the dependence on z of the coordinate $x = R(z)$ which describes the surface AB. Then the problem (3) is easily solved by the method of separation of variables. For a plane jet we have

$$\begin{gathered} \varphi = -\frac{8\alpha}{\pi^2}\,\bar{u}^0 H \sum_{n=1}^{\infty} \frac{\cos\omega_n z}{(2n-1)^2}\,\frac{\exp(-\omega_n x) + \exp[-\omega_n(2L - x)]}{\exp(-\omega_n R) + \exp[-\omega_n(2L - R)]}, \\ u_x' = -\frac{4}{\pi}\,u^0 \sum_{n=1}^{\infty} \frac{\cos\omega_n z}{2n-1}\,\frac{\exp(-\omega_n x) - \exp[-\omega_n(2L - x)]}{\exp(-\omega_n R) + \exp[-\omega_n(2L - R)]}, \\ u_z' = -\frac{4}{\pi}\,u^0 \sum_{n=1}^{\infty} \frac{\sin\omega_n z}{2n-1}\,\frac{\exp(-\omega_n x) + \exp[-\omega_n(2L - x)]}{\exp(-\omega_n R) + \exp[-\omega_n(2L - R)]}, \\ \omega_n = \frac{(2n-1)\,\pi}{2H}. \end{gathered} \tag{5}$$

*The shape of the surface BC can be found in principle from the solution of (4). The shape of the surface AB must be determined from the solution of the problem of internal flow in the jet channel.

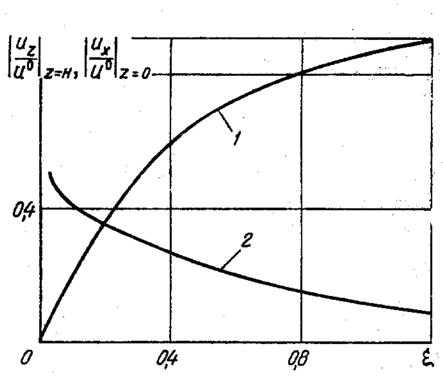

Fig. 3.

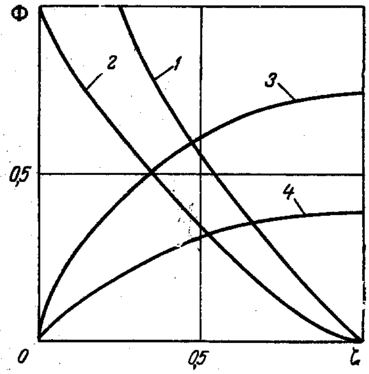

Fig. 4.

Fig. 3. Dimensionless gas velocity at exit from bed in vicinity of jet (curve 1) and velocity of inflow of gas toward base of jet along gas-distribution grid (curve 2) as functions of the dimensionless horizontal coordinate.

Fig. 4. Distribution of horizontal components of relative gas velocity and particle velocity at surface of jet channel: 1) $\Phi = |u_x/u^0|$; 2) $\Phi = |w_x/w_*|$; 3) $\Phi = Q_u/u^0 H\varepsilon$; 4) $\Phi = Q_p/w_* H\rho$.

Adding the last two series, in the case of a single jet ($L \to \infty$) we obtain

$$u'_x = -\frac{1}{\pi} u^0 \ln \frac{\{[1-\exp(-\pi\xi)]^2 + 4\exp(-\pi\xi)\sin^2(\pi\zeta/2)\}}{[1+\exp(-\pi\xi) - 2\exp(-\pi\xi/2)\cos(\pi\zeta/2)]^2},$$
$$u'_z = -\frac{2}{\pi} u^0 \operatorname{arctg} \frac{\exp(-\pi\xi/2)\sin(\pi\zeta/2)}{1-\exp(-\pi\xi)}, \quad \xi = \frac{x-R}{H}, \quad \zeta = \frac{z}{H}. \tag{6}$$

A study of Eqs. (6) shows that there is considerable injection of gas into the jet. The dependence on the dimensionless horizontal coordinate ξ of the quantities $u_z/u^0|_{z=H}$ and $u_x/u^0|_{z=0}$ obtained from (6) is shown in Fig. 3. The first of these characterizes the relative velocity of the gas at the exit from the fluidized bed and the second characterizes the inflow of gas toward the base of the jet channel along the gas-distribution grid. It is seen that regardless of its horizontal size R the jet exerts a considerable influence on the internal hydrodynamics of the bed, extending to distances having the order of the bed height H.

The relative velocity of the gas at the boundary $x = R$ of the jet channel is of particular interest. From (3) and (6) we have

$$u_x|_{x=R} = u'_x|_{x=R} = -\frac{2}{\pi} u^0 \ln \operatorname{ctg} \frac{\pi\zeta}{4}, \quad u_z|_{x=R} = 0. \tag{7}$$

This equation also determines the density of the gas stream in the jet due to its motion relative to the disperse phase. For a plane jet the total volumetric flux of injected gas entering the section of the jet channel from the grid to the level z and connected with the relative gas flow equals

$$2Q_u(z) = -2\varepsilon \int_0^z u_x|_{x=R}\, dz = \frac{16u^0 H\varepsilon}{\pi^2} \int_0^{\pi\zeta/4} \ln \operatorname{ctg} t\, dt = \frac{16u^0 H\varepsilon}{\pi^2}\left[L\left(\frac{\pi}{2}\right) - L\left(\frac{\pi\zeta}{4}\right) - L\left(\frac{\pi}{2} - \frac{\pi\zeta}{4}\right)\right]. \tag{8}$$

In particular,

$$2Q_u(H) = \frac{16G}{\pi^2} u^0 H\varepsilon, \quad G \approx 0.916. \tag{9}$$

Here L(t) is the Lobachevskii function and G is the Catalan constant. The dependence of the quantity u_x from (7) and Q_u from (8) on ζ is shown in Fig. 4. It is seen that the gas flux density in the jet channel decreases monotonically with an increase in height above the grid.

The solution of problem (4) is complicated by the fact that neither the shape of the boundary surface ABC nor the functions $Q_s(r)$ and $\Pi_s(r)$ characterizing the arrival of particles at the free surface of the bed are known. However, an approximate estimate can be obtained for the particle velocity at the boundary of the jet channel without resorting to an exact solution of (4). Using (3) and the definition of u_0 in (2) and integrating the first equation of (4) along the streamlines of the disperse phase, we obtain the following analog of the Bernoulli equation:

$$w^2 = -\frac{2}{\rho d_1}(P+\varphi) + F(\psi) = 2g(H-z) - \frac{2P}{\rho d_1} + F(\psi), \tag{10}$$

where $F(\psi)$ is some function of the stream function ψ of the disperse phase which is reduced to zero far from the jet. According to the boundary condition in (4), at the boundary AB the quantity P is equal to zero, so that from (10) we get the estimate

$$w|_{x=R} = [2gH(1-\zeta) + F(\psi)]^{1/2} \approx w_* \sqrt{1-\zeta}, \quad w_* = \sqrt{2gH}. \tag{11}$$

The approximate equality in (11) is obtained with neglect of $F(\psi)$, which is justified for the lower and central parts of the channel $(1-\zeta \sim 1)$, into which most of the mass of injected particles enters.

Because of the inertia of the particles the streamlines of the disperse phase deviate from the streamlines of the flow whose velocity components are determined in (5) and which is superimposed on the undisturbed flow of a gas with $u_x^0 = 0$ and $u_z^0 = u^0$. In obtaining order-of-magnitude estimates of the velocity components of the disperse phase at the channel boundary these deviations, like the influence of the forces of adhesion between particles, can be neglected. Then from (7) and (11) we obtain the expressions

$$w_x|_{x=R} \approx -w_* \sqrt{1-\zeta}\,\ln\operatorname{ctg}\frac{\pi\zeta}{4}\left(\ln^2\operatorname{ctg}\frac{\pi\zeta}{4} + \frac{\pi^2}{4}\right)^{-1/2},$$

$$w_z|_{x=R} \approx -\frac{\pi}{2} w_* \sqrt{1-\zeta}\left(\ln^2\operatorname{ctg}\frac{\pi\zeta}{4} + \frac{\pi^2}{4}\right)^{-1/2}. \tag{12}$$

The flux of the disperse phase within the section of the jet channel from the grid to the level z turns out to equal

$$2Q_p(z) \approx -2\rho\int_0^z w_x|_{x=R}\,dz = 2w_*H\rho\int_0^\zeta \frac{\sqrt{1-t}\,\ln\operatorname{ctg}\pi t/4}{(\ln^2\operatorname{ctg}\pi t/4 + \pi^2/4)^{1/2}}\,dt. \tag{13}$$

In particular, the total volumetric flux of particles into the jet is

$$2Q_p(H) \approx 2w_*H\rho\int_0^1 \frac{\sqrt{1-t}\,\ln\operatorname{ctg}\pi t/4}{(\ln^2\operatorname{ctg}\pi t/4 + \pi^2/4)^{1/2}}\,dt \approx 0.77 w_* H\rho. \tag{14}$$

The dependence of w_x from (12) and Q_p from (13) on ζ are also presented in Fig. 4. We note that the quantity Q_p, which characterizes the intensity of particle circulation induced by the gas jet, is proportional to $H^{3/2}$. The total gas flux into the jet channel is made up of the relative flux $2Q_u$ determined in (8) and the flux corresponding to flow with the velocity of the disperse phase. Thus,

$$2Q_f(z) = 2Q_u(z) + \frac{\varepsilon}{\rho}\,2Q_p(z). \tag{15}$$

Let us analyze qualitatively the dependence of the dimension R and the gas velocity V in the jet channel on the vertical coordinate, using for this purpose the conditions of integral balance of volume and impulse in the channel cross sections. The equation of volume balance has the form

$$\langle \varepsilon' V\rangle R + \langle \rho'(V-U)\rangle R = V_0R_0 + Q_f + Q_p, \tag{16}$$

where the angular brackets denote averaging over a cross section of the jet channel.

Similarly, the balance equation for the vertical component of the impulse has the form

$$d_0\langle \varepsilon' V^2\rangle R + d_1\langle \rho'(V-U)^2\rangle R = d_0V_0^2R_0 - d_1\Pi_p, \tag{17}$$

$$\Pi_p(z) = \rho\int_0^z w_xw_z|_{x=R}\,dz = \frac{\pi}{2}\rho w_*^2 H\int_0^\zeta \frac{\ln\operatorname{ctg}\pi t/4}{\ln^2\operatorname{ctg}\pi t/4 + \pi^2/4}\,dt,$$

where the vector sum of the initial impulse of the jet and the impulse imparted to it by the particles (the injected gas flows into the channel normal to its boundary, so that the vertical component of the impulse imparted by it is approximately equal to zero) figures in the right side of (17). We note that in (16) and (17) it is assumed that $\rho' \ll 1$ and that the dynamic relaxation time of the particles is small; therefore, one can assume that the particle velocity is equal to the local gas velocity after subtraction of the velocity of floating of a single particle in a uniform stream. Equations (16) and (17) must be supplemented by the condition of particle balance in the jet channel:

$$\langle \rho' (V - U) \rangle R = Q_p. \tag{18}$$

The calculation of the average quantities in (16)-(18) requires knowledge of the details of the particle distribution over the cross section of the jet channel and of the gas velocity profile in it. With the intention of obtaining order-of-magnitude estimates, we take

$$\langle \varepsilon' V \rangle \sim \varepsilon' V, \quad \langle \varepsilon' V^2 \rangle \sim \varepsilon' V^2,$$

henceforth understanding ε' and V to be averages over the channel cross section of the porosity and gas velocity.

Using the inequality $\rho' = 1 - \varepsilon' \ll 1$, we then rewrite (16)-(18) in the form

$$\begin{gathered} VR - V_0 R_0 \sim Q_f, \\ V^2 R - V_0^2 R_0 \sim -\frac{d_1}{d_0}(V + W - U) Q_p, \quad W = \frac{\Pi_p}{Q_p}, \end{gathered} \tag{19}$$

where W is some effective velocity characterizing the impulse imparted to the jet channel by the injected particles, and which depends, of course, on z. The solution of (19) gives

$$\begin{gathered} \frac{V}{V_0} \sim \left(1 + \frac{d_1}{d_0}\frac{U-W}{V_0}\frac{Q_p}{V_0 R_0}\right)\left(1 + \frac{Q_f}{V_0 R_0} + \frac{d_1}{d_0}\frac{Q_p}{V_0 R_0}\right)^{-1}, \\ \frac{R}{R_0} \sim \left(1 + \frac{Q_f}{V_0 R_0}\right)\left(1 + \frac{Q_f}{V_0 R_0} + \frac{d_1}{d_0}\frac{Q_p}{V_0 R_0}\right)\left(1 + \frac{d_1}{d_0}\frac{U-W}{V_0}\frac{Q_p}{V_0 R_0}\right)^{-1}. \end{gathered} \tag{20}$$

Using (20) and the other equations it is not hard to obtain the dependence of the average gas velocity in the jet and to construct the channel profiles for different values of the parameters. As follows from (20), the quantities V/V_0 and R/R_0 are determined by the independent dimensionless parameters

$$\frac{d_1}{d_0}, \quad \frac{U-W}{V_0}, \quad \frac{Q_f}{V_0 R_0}, \quad \frac{Q_p}{V_0 R_0},$$

the physical meaning of which is obvious.

If the initial velocity of the jet is high, so that one can take $U \sim u^0 \ll V_0$, $w_* \ll V_0$, $u^0 H \ll V_0 R_0$, and $w_* H \ll V_0 R_0$, then Eqs. (20) are considerably simplified. We have

$$\frac{V}{V_0} \sim \left(1 + \frac{d_1}{d_0}\frac{Q_p}{V_0 R_0}\right)^{-1}, \quad \frac{R}{R_0} \sim 1 + \frac{d_1}{d_0}\frac{Q_p}{V_0 R_0}. \tag{21}$$

The jet profiles for different values of V_0 and w_* are easily obtained using the $Q_p(z)$ curve in Fig. 4.

In conclusion, we note that the analysis of axisymmetric jets does not introduce complications of a fundamental order, but the purely computational difficulties prove to be very considerable. Therefore, such an analysis, like the study of the constrained flow formed by a system of plane or axisymmetric jets, can comprise the subject of an independent report.

NOTATION

d_0, d_1, gas and particle densities; F, unknown function in (11); g, acceleration of gravity; H, height of bed; L, external dimension of bed; P, pressure of disperse phase; p, gas pressure; Q_u, Q_f, Q_p, half-values of relative gas flux and of total volumetric fluxes of fluid and disperse phases into jet, respectively; Q_s, volumetric flux of particles onto free surface of bed; R, half-width of jet channel; U, velocity of floating; u, relative gas velocity in spaces between particles; V, gas velocity in jet; v, gas velocity in spaces between particles; W, w_*, characteristic velocities introduced in (12) and (20); w, velocity of disperse phase; x, z, coordinates; α, coefficient to resistance force in (1); ε, ε', porosities in compact phase of bed and in jet channel; ξ, ζ, dimensionless coordinates determined in (6); Π_s, Π_p, functions introduced in (4) and (19), respectively; ρ, ρ', volumetric particle concentrations in compact phase and in jet channel; φ, excess pressure; ψ, stream function of disperse phase; ω_n, eigenvalues. Indices: zero superscript, gas flow in the bed undisturbed by the jet; zero subscript, initial parameters of the jet.

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EXPERIMENTAL DETERMINATION OF THE STATISTICAL CHARACTERISTICS OF GAS MOTION IN A FLUIDIZED BED

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A method is proposed for the determination of the statistical characteristics of the gas motion in a fluidized bed by the pneumatometric method. The dependences of these characteristics on the parameters of the process are obtained.

The experimental determination of the statistical characteristics of any random process encounters an important difficulty consisting in the fact that the measuring system distorts the fluctuations of the parameter under study because of the influence of its frequency properties. In many cases it is impossible to reconstruct the actual form of the realization, even when one has data on the dynamic properties of this system.

However, the problem of the experimental determination of the statistical characteristics of the fluctuations of any parameter can be solved without reconstructing the actual form of the realization. The methods of mathematical statistics [1] allow one to find them from the statistical characteristics of the distorted realization, taking into account the dynamic properties of the measuring system.

For the measurement of the instantaneous gas velocity in a fluidized bed we chose the pneumatometric method, which is distinguished by the simplicity and accessibility of the fabrication and calibration of the pickups and the reliability in operation. But when using this method one must allow for the distortions introduced by the measuring system, which can be divided arbitrarily into two types. The first type is the distortions connected with the presence of solid particles in the stream. The average gas velocities calculated from the readings of the pneumatometric probe prove to be overstated [2, 3, 4]. The second type of distortions is connected with the inertia of the measuring system and can be allowed for by an experimental determination of its amplitude–frequency characteristic curve.

A low-inertia Pitot–Prandtl tube, whose length together with the connecting channels was 150 mm and whose diameter was 2 mm, was used in our experiments. A membrane differential manometer made in conjunction with the tube served as the secondary instrument. The membrane movements were measured by an electronic system [5] using a 6MKh1S mechanotron. The pulsations were recorded on photographic film by a light-beam oscillograph. The graphs were quantified with a Siluét automatic reader. The data obtained from the Siluét instrument in five-track telegraphic code were processed in an Odra-1204 computer. The amplitude–frequency characteristic curve of the measuring system was taken by the method of supplying a unit jump to its input. The numerical values of the amplitude–frequency characteristic curve are as follows:

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