EXPERIMENTAL STUDY OF THE MOTION OF SOLID PARTICLES IN A TURBULENT GAS FLOW. THE TRANSFER MECHANISM

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A model accounting for particle interaction with channel walls and collisions between particles is proposed on the basis of analysis of experimental particle-velocity distribution functions.

A flow of a gaseous suspension is usually interpreted [1, 2] as independent motion by individual particles caused by their interaction with the conveying medium and the participation of the latter in the pulsative motion. Meanwhile, the transport of particles in a two-phase flow is also governed by the chaotic motion of the solid phase [3]. According to data from experimental studies of horizontal [4, 5] and vertical [6-8] gas-suspension flows, the motion of the solid particles is accompanied by large-scale fluctuations of the velocity components, comparable in magnitude with the average velocity. For sufficiently large particles (0.5-1 mm) — the participation of which in the pulsative motion of the conveying medium is negligible [1] — the chaotic motion is due mainly to their collision with one another and with the walls of the channel. In this respect, the two-phase flow represents a stochastic system. Determination of the laws governing its motion requires information on the particle-velocity distribution functions at different points of the flow cross section. There is currently no such data available; only certain models have been published [9-11]. These models describe the character of motion of solid particles in a vertical gas-suspension flow and are based on study of the interaction of the solid particles with the channel walls.

To study the structure of two-phase flows, we developed a small contact-type piezoelectric transducer and an instrument set [12] which make it possible to reliably measure simultaneously the mechanical interaction and density of a flow of solid particles. Amplitude spectra were recorded with 100-channel analyzer AI-100-1, which operates on the principle of channel separation of the initial semisinusoidal signals of the transducer. The signal interval corresponded to the resolution of the transducer, which was 0.025 m/sec according to calibration data. The construction of histograms of the amplitude spectra was monitored in each experiment on the screen of the cathode-ray analyzer, and the independence of a given spectrum was determined from the satisfaction of the condition of steadiness of the weighted-mean amplitude $\bar{a}$:

$$\bar{a} = \frac{1}{N} \sum_{i=1}^{N} a_i m_i = \text{const.} \tag{1}$$

Two frequency meters were added to the measurement circuit to check for the satisfaction of condition (1) in real time. One of these meters recorded the quantity $\sum_{i=1}^{N} a_i m_i$, while the second meter recorded the total number of recorded particles N. A dual-trace recording oscillograph was used to adjust the circuit parameters and verify the measurement.

The studies were conducted with a narrow fraction of glass spheres 1.0-1.25 mm (mean diameter d = 1.18 mm) on the stabilized section of an ascending flow in a pipe of the diameter D = 2R = 50 mm. The flow-rate concentration μ_f and velocity of the conveying medium $\overline{w}$ were varied within the ranges 0.2-16 kg/h/kg/h and 13-23.5 m/sec, respectively. It should be emphasized that condition (1) was satisfied when there was from 5000 to 30,000 recorded particles. The time required to realize one spectrum here ranged from 100 to 300 sec. We measured

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local spectra of the axial velocity component and the density of the flow (flux) of solid particles across the channel diameter at distances 0, 5, 10, 15, 20, and 23 mm from the center of the channel. We also measured the frequency of collisions and spectra of the radial velocity component of the particles at the channel wall.

The measurements showed that the two-phase flow is characterized by disordered motion of the solid phase, with a random change in the instantaneous velocity values in time and space. Figure 1 shows typical experimental curves of the probability density of the longitudinal $P(u_z)$ (a–d) and transverse $P(u_r)$ (e, f) components of the instantaneous velocity of the particles. We should point out the extent of the range of fluctuation of the velocity components. The range of the u_z curves on the right reaches the limiting steady-state velocity of a single particle in an infinite space $u_z = \bar{w} - v$. (Curve 5 in Fig. 1 is given with allowance for the granulometry of the investigated solid-particle fraction. It is easy to see that the slight dispersion of the limiting distribution curve can be ignored in subsequent analysis.) A characteristic feature of the local particle distribution functions for axial velocity is the slight deviation from the normal distribution law at low concentrations of the flow and the presence of a second maximum at high concentrations (the second maximum is more distinct as $\bar{w}$ increases). Analysis of the curves $P(u_z)$ at different points of the channel cross section (Fig. 1, a–d) shows that the spatial statistical pattern of particle motion is uniform and is independent of the radial coordinate — at least up to distances from the pipe wall of 1.5–2 particle diameters. The observed quantitative changes in the distribution functions over the channel radius (smoothing of the second maximum, decrease in the most probable particle velocity near the wall) are due to interparticle collisions (see below).

The data on the radial velocity distribution functions of the particles $P(u_r^+)$ at the channel wall (Fig. 1, e and f) characterize the transverse migration of the particles from the axis of the flow (the direction of flow being taken as the positive direction) to its periphery. It is clear from the obvious triviality of the total particle flow over any cylindrical surface that the functions $P(u_r)$ decay into two individual distributions $P(u_r^+)$ and $P(u_r^-)$ for the positive and negative components of transverse velocity, respectively. In our opinion, this fact is a manifestation [see the left branch of the curves $P(u_r^+)$] of one of the important aspects of the mechanism of solid-particle motion in a two-phase flow: it is not likely that particles with angles of incidence which are close to zero will interact with the channel wall.

It is worth noting that, according to measurements made in a fluidized bed [13], probability density curves for circulation contours also decay into two distributions.

The functions $P(u_r^+)$ are quite different from the normal distribution law. The asymmetry coefficient A and excess coefficient E are always positive and increase in proportion to increases in the flow-rate concentration. The quantities A and E take values A = 1–2.5 and E = 0.5–15.5 in the range μ_f = 1–15 and are nearly independent of the velocity of the conveying medium.

Knowledge of the statistical functions $P(u_z)$ and $P(u_r)$ makes it possible to correctly determine (Fig. 2) the mean values of longitudinal $\bar{u}_z$ and transverse $\bar{u}_r$ velocity at given points of the radial coordinate and the dispersion of the distributions (in physical terms, the latter corresponds to the standard deviation of the pulsative components of local particle velocity $\bar{u}_z'$ and $\bar{u}_r'$).

Given the conditions of motion of the two-phase flow, the axial velocity of the particles $\bar{u}_z$ is considerably less than the limiting value calculated with allowance for the free-fall velocity of one particle. Here, phase slip $(\bar{w} - \bar{u}_z)$ increases with an increase in the velocity of the conveying medium. These conclusions are in qualitative agreement with the data obtained in numerous studies of particle velocity in ascending flows of gaseous suspensions [6, 7, 8] and can be completely substantiated physically using representations of momentum loss in the impact interaction of the particles with the channel walls.

It follows from Fig. 2 that an increase in μ_f leads to an increase in particle velocity. In the range μ_f = 1–15, the value of $\bar{u}_z$ increases by a factor of 1.5. It should be noted that there are no recommendations in the literature regarding the relation $u_z(\mu_f)$. In our opinion, this is due to the fact that, in most studies, the flow concentration was too low $(\beta \leqslant 1 \cdot 10^{-3})$ and there were not enough realizations of the random variable u_z (m = 15–100) for reliable averaging.

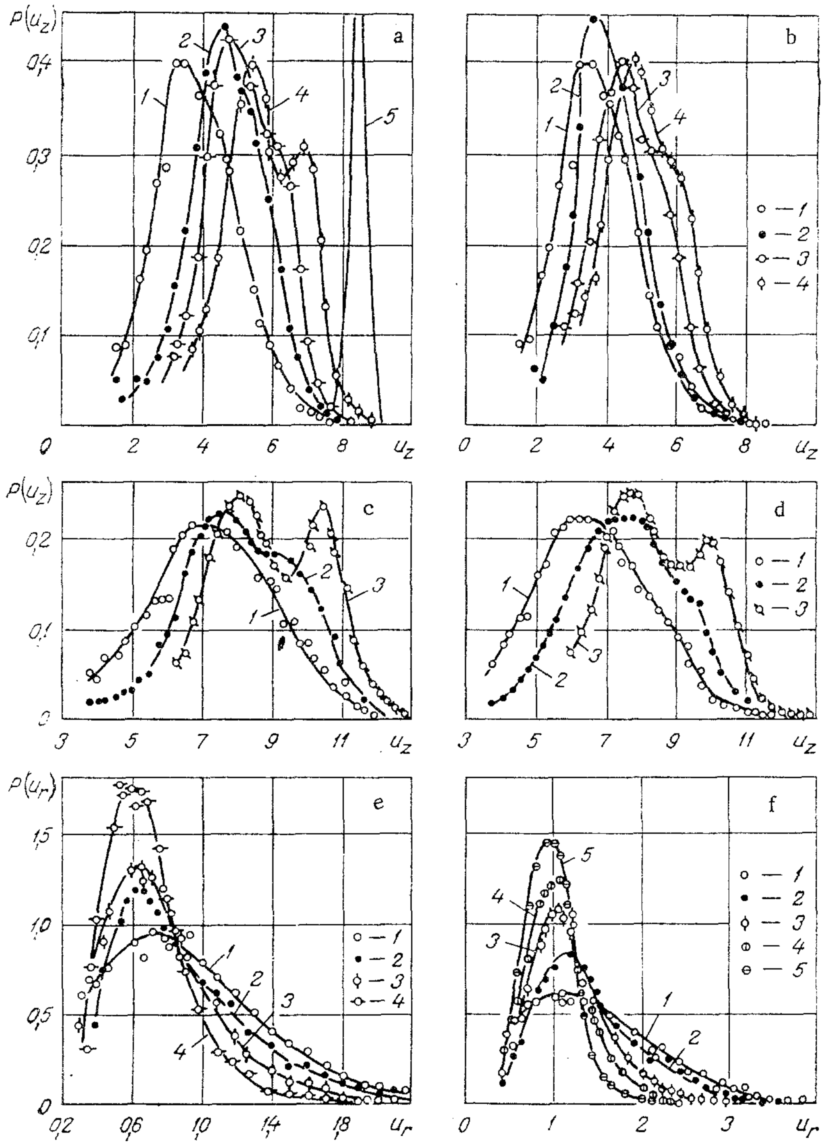

Fig. 1. Probability density curves of longitudinal (a–d) and transverse (e, f) components of instantaneous velocity of the solid particles: a, c) at center of channel, r = 0; b, d) r = 23 mm; a, b) $\bar{w}$ = 16.5 m/sec; 1) μ_f = 0.7 kg/h/kg/h; 2) 2.5; 3) 6.7; 4) 9.5; 5) limiting velocity of one particle; c, d) $\bar{w}$ = 23.3 m/sec; 1) μ_f = 0.9 kg/h/kg/h; 2) 3.3; 3) 8.6; e) $\bar{w}$ = 16.5 m/sec; 1) μ_f = 0.9 kg/h/kg/h; 2) 3.7; 3) 5.5; 4) 9.6; f) $\bar{w}$ = 23.3 m/sec; 1) μ_f = 1 kg/h/kg/h; 2) 3.3; 3) 6.7; 4) 10.8; 5) 16.5. $P(u_z)$; $P(u_r)$, $m^{-1}\cdot$sec; u_z; u_r, m/sec.

The extensive data in [1] on the decrease in the rate of interphase heat exchange with an increase in the concentration of the gas-suspension flow is indirect confirmation of the derived relation $u_z(\mu_f)$. This data has not yet been reliably verified. The above facts concerning the relation $u_z(\mu_f)$ cannot be explained within the framework of general representations of the change in the regime of fluid flow about particles in the case of constrained flow. Thus, the reduction in free-fall velocity (calculated with O. M. Todes' formula [1]) and the corresponding increase in the limiting velocity of a constrained particle flow at $\beta \approx 2\cdot10^{-2}$ (corresponding to the maximum solid-phase loads in the present work) do not exceed 5%.

In our opinion, the decrease in slip velocity and the rate of various transfer phenomena in the case of constrained particle flow is attributable to the total effect of the processes associated with the interactions among the particles and between the particles and the channel walls.

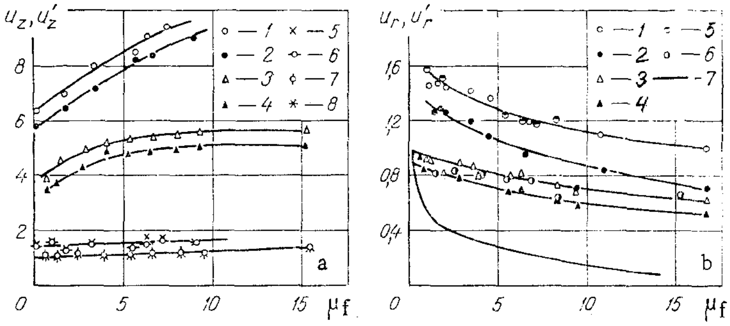

Fig. 2. Dependence of average and pulsative components of particle velocity on flow concentration: a) longitudinal velocity components; 1-4) average velocities; 5-8) pulsative velocities; 1,2,5,6) $\bar{w}$ = 23 m/sec; 3,4,7,8) $\bar{w}$ = 16.5 m/sec; 1,3,5,7) center of channel, r = 0; 2,4,6,8) r = 23 mm; b) transverse velocity components; 1,3) average velocities; 2,4) pulsative velocities; 1,2) $\bar{w}$ = 23.3 m/sec; 3,4) $\bar{w}$ = 16.5 m/sec; 5,6) calculation with Eq. (9); 7) calculation with Eq. (4). u_z, u_z', u_r, $\bar{u}_r'$, m/sec; μ_f, kg/h/kg/h.

Before examining the "collision" processes in detail, let us briefly look at the main results of studies of the transverse migration of relatively coarse particles in an ascending gas-suspension flow. The frequency of collision of a disperse material with channel walls was studied in [9]. Assuming that the projection of the trajectory of the mean transverse particle velocity $\bar{u}_r$ on a horizontal plane coincides with the middle chord of the channel $L = 2D/\pi$, the authors obtained an equation for the mean time between two successive particle collisions with the wall:

$$\Delta\tau = 2D/\pi\bar{u}_r. \quad (2)$$

Then using the following expression, which is obvious for equiprobable motion of all particles,

$$\Delta\tau = \frac{3D\bar{w}\rho\mu_f}{2\pi u_z\rho_p d^3 g_r}, \quad (3)$$

it is easy to find the connection between the quantities g_r and $\bar{u}_r$:

$$\bar{u}_r = \frac{4u_z\rho_p d^3 g_r}{\bar{w}\rho\mu_f}. \quad (3)$$

As is shown in Fig. 2b, using empirical data on particle flux to the wall g_r and axial particle velocity u_z — qualitatively reflecting the form of the relation $\bar{u}_r(\mu_f)$ — one can employ one-velocity model (2), (4) to evaluate only the order of the mean transverse velocity. This model agrees quantitatively with the empirical results only in the region of very low concentrations $\mu_f < 1$.

The difference between values of g_r and $\bar{u}_r$ calculated with (2), (4) and obtained experimentally, noted in [10], was the reason for developing a two-velocity model of solid particle motion [11]. The model is based on the tentative delineation of a certain central zone of the flow in which the particles (I) move with high axial and negligibly low transverse velocities and do not collide with the wall. The flow also contains particles (II) which intensively collide with the wall. The character of the motion and the concentration of these particles and the flow as a whole is determined by Eqs. (2) and (4). It is assumed that only particles of a different kind can collide, and that the probability of collisions of particles I and II during a period of time $\Delta\tau$ is not high. As a result, we obtain a system of equations, numerical solution of which enables determination of the axial velocities and concentrations of the particles I and II so as to agree with experimental values of g_r and $\bar{u}_r$.

Separation of the flow into two kinds of particles with sharply differing types of motion is confirmed neither by data from detailed statistical analysis of the fields of mean and pulsative velocity u_z and u_z' (Figs. 1 and 2) nor by the parameters of distribution functions of the time intervals between the successive passage of particles at different fixed points of the flow cross section [12].

A serious and common shortcoming of the above models is the assumption, expressed by Eq. (2), that the horizontal projection of the particle trajectory coincides in the time interval $\Delta\tau$ with the middle chord of the channel (regardless of μ_f). Such an assumption neglects interparticle collisions and the effect of this factor on formation of the mean and random motions of the flow.

In actuality, particles having any velocity within the range of possible velocities u_{min}–u_{max} take part in collisions. In accordance with the representations of kinetic molecular theory [14], the frequency of collision of particles moving with velocities u_i and u_k is determined by the equation

$$\nu = \pi d^2 |u_i - u_k| \cdot n. \tag{5}$$

Particle direction changes with each collision, so the volume $\pi d^2 |u_i - u_k|$ "expressed" by the particle in space is equal to the sum of the volumes of as many cylinders as there are collisions experienced by the particle per second. In accordance with Eq. (5), the frequency of collision of particles moving with the velocities $\bar{u}_z$ and $\bar{u}_r$ at any point of the channel cross section can be represented as the sum of the frequencies from the axial $P(u_z)$ and radial $P(u_r)$ particle velocity spectra

$$\nu(r) = \pi d^2 \left[\frac{g_z(r)}{u_z(r)} \int_{u_{min}}^{u_{max}} |\bar{u}_z - u_z| \cdot P(u_z)\, du_z + \frac{g_r}{u_r} \int_{u_{min}}^{u_{max}} |\bar{u}_r - u_r| \cdot P(u_r) du_r + 2g_r \right]. \tag{6}$$

The third term of Eq. (6) describes the frequency of collisions from counter-directed motion of particles in the radial direction, the particles having the velocities u_r^+ and u_r^-.

Figure 3 shows results of calculation of the fields of collision frequencies for different μ_f and $\bar{w}$. The quantity n was calculated from measurements of local particle flux and axial velocity, while the quantities g_r and u_r were calculated from measurements at the channel wall. It should be noted that $g_z \approx 5\text{–}100 \cdot 10^6$ particles/m²·sec and $g_r \approx 0.3\text{–}3 \cdot 10^6$ particles/m²·sec under the conditions of the experiment.

In essence, the relation $\nu(r)$ differs from $g_z(r)$, $\mu(r)$, and $\beta(r)$ only in the scale factors and reflects the general character of the solid-particle distribution across the channel: a nearly uniform distribution at low μ_f and a distribution with a maximum in the core of the flow with high μ_f.

Figure 4 shows mean (across the channel) frequencies of interparticle collisions and the frequency of particle collision with the wall $\nu_{wa} = \Delta\tau^{-1}$ [calculated from Eq. (3)] in relation to the constraint of the flow μ_f. We may note the opposite character of the relations $\bar{\nu}(\mu_f)$ and $\nu_{wa}(\mu_f)$. The consequence of the mutual shielding effect is an increase in the length of the path traveled by the particles between collisions with the wall and, thus, an increase in particle axial velocity — see the experimental results for u_z (Fig. 2).

Within the framework of the motion model being examined, the horizontal projection of the particle trajectory over the time $\Delta\tau$ can be expressed through the path length l between interparticle collisions:

$$L = l\bar{\nu}\Delta\tau. \tag{7}$$

According to Eq. (7), the length L, increasing with an increase in μ_f, may by several times exceed the value of L, calculated with Eq. (2).

For an independent (of the measured values of u_r) determination of l, we will use the representation of this quantity in kinetic-molecular gas theory [14]:

$$l = 1/\pi \sqrt{2} d^2 n. \tag{8}$$

Then, from Eq. (7), (8), and (3), we obtain the equations:

$$u_r = \frac{\bar{\nu} u_z}{\pi \sqrt{2} d^2 g_z}; \quad \frac{\bar{\nu}}{\nu_{wa}} = \frac{3 u_r g_z D \beta}{\sqrt{2} u_z g_r d}. \tag{9}$$

Comparison of values of transverse particle velocity calculated from (9) and measured (Fig. 2b) shows the adequacy of the proposed model to describe the motion of the discrete phase within a broad range of parameters for the two-phase flow.

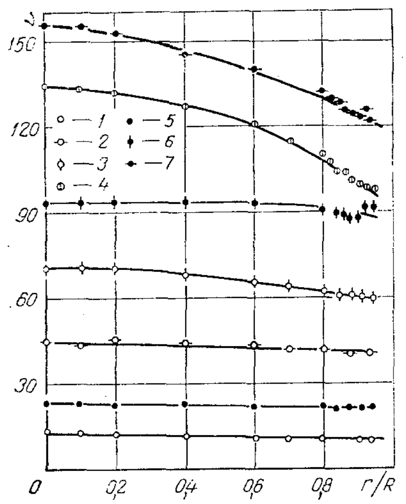

Fig. 3

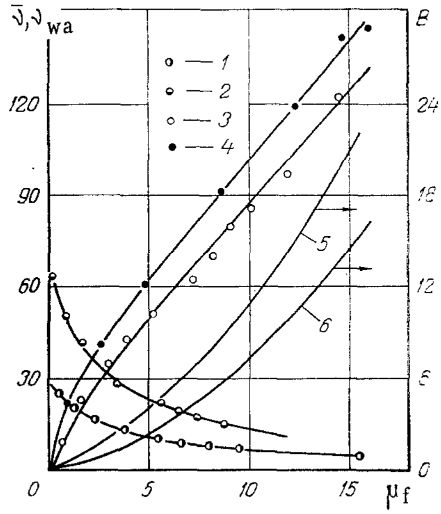

Fig. 4

Fig. 3. Radial distribution of frequency of interparticle collisions: 1-4) $\bar{w}$ = 16.5 m/sec; 5-7) $\bar{w}$ = 23.3 m/sec; 1) μ_f = 0.7 kg/h/kg/h; 2) 3.99; 3) 7.95; 4) 14.5; 5) 0.98; 6) 7.9; 7) μ_f = 14.85 kg/h/kg/h. ν, sec^{-1}.

Fig. 4. Dependence of collision frequency on flow concentration: 1, 2) collisions with wall; 3,4) interparticle collisions; 5,6) interaction parameter; 1,3,5) $\bar{w}$ = 16.5 m/sec; 2,4,6) $\bar{w}$ = 23.3 m/sec. ν, ν_{wa}, sec^{-1}; μ_f, kg/h/kg/h.

Analysis of data from the statistical study of structural and dynamic characteristics of the mean and random motion of solid particles revealed a quantitative measure of individual modes of motion of a two-phase flow. For this measure, the parameter $B = \bar{\nu}/\nu_{wa}$ was introduced in (9). This parameter expresses the total effect of the collisions. When B < 1 (curves 5 and 6 in Fig. 4), flow motion is controlled mainly by particle interaction with the channel wall. This range is characterized by the most chaotic structure: the velocity distribution functions $P(u_z)$ and $P(u_r)$ are close to being normal; the pulsative velocity components $\overline{u'_z} \approx u'_r$ are isotropic; particle distribution across the channel is nearly uniform. It should be noted that representations of independent particle motion are correct only within the concentration range B < 1. In this case, particle motion can be described with allowance for momentum loss on the wall.

The process of interparticle collision begins to dominate with an increase in μ_f. The region B > 1 is characterized by high axial velocity and impeded radial migration of the particles. Significant anisotropy of the pulsative velocities is seen. As a result of an increase in the frequency of interparticle collisions, the pulsative velocity u'_z of some of the particles may substantially exceed the mean value $\overline{u'_z}$. The connection between the second maximums on the probability density curves $P(u_z)$ and the quantity ν is evidenced by the increase in these maximums with an increase in the velocity of the conveying medium and their leveling in accordance with the radial frequency curves for interparticle collisions (Fig. 3).

An increase in the velocity of the conveying medium is accompanied by a shift in the upper limit of the regime B < 1 to the region of higher flow concentrations. When $\bar{w}$ = 23 m/sec, $\mu_f \approx 2$. The transition from the region B < 1 to the region B > 1 is accompanied by a monotonic change in the angle of incidence of the particles relative to the wall from about 17° at $\mu_f \sim 1$ to about 6° at $\mu_f \sim 15$.

Thus, the introduction of an interaction parameter makes it possible to concretize and significantly expand representations of the conditions of motion of an ascending two-phase flow advanced earlier [15] in a study of the velocity fields of the conveying medium.

The direction and results of the present study make it possible to proceed to a substantiated description of diffusional parameters of the motion of solid particles in an ascending two-phase flow and the drag and structure of such a flow. However, these and related topics will require special investigation.

NOTATION

μ_f, β, flow-rate and volume concentrations of two-phase flow; $\bar{w}$, mean gas velocity in pipe; u_z, u_r, longitudinal and transverse velocities of particles; u'_z, u'_r, pulsative components of particle velocity; v, free-fall velocity; d, particle diameter; D, channel diameter; r, current radius; a, amplitude of impulse; $\Delta\tau$, time interval between successive particle collisions with wall; L, horizontal projection of particle path over the time $\Delta\tau$; l, free path length of particles; ρ, ρ_p, densities of gas and solid particles; g_z, g_r, particle flux; n, number of particles per unit volume; ν, frequency of interparticle collisions; ν_{wa}, frequency of particle collisions with wall.

LITERATURE CITED

1. Z. R. Gorbis, Heat Exchange and the Hydrodynamics of Disperse Through Flows [in Russian], Énergiya, Moscow (1970).
2. R. Busroid, Gas Flow with Suspended Particles [Russian translation], Mir, Moscow (1975),
3. R. I. Nigmatulin, Principles of the Mechanics of Heterogeneous Media [in Russian], Nauka, Moscow (1978).
4. R. Eikhorn, R. Shanni, and U. Navon, "Determination of the velocity of the solid phase in the turbulent pipe flow of a gas suspension," in: Heat and Mass Transfer [in Russian], Vol. 5, Énergiya, Moscow—Leningrad (1968), pp. 274-291.
5. Maeda Masanoby and Ikai Shigeru, "Pneumatic conveying of solids," Bull. Jpn. Mech. Eng., 13, No. 65, 1308-1315 (1970).
6. K. V. S. Reddy and O. C. T. Pei, "Particle dynamics in solids—gas flow in a vertical pipe," Ind. Eng. Chem. Fund., 8, No. 3, 490-497 (1969).
7. Maeda Masanobu, Ikai Shigeru, and Ukon Atsuo, "Pneumatic conveying of solids," Bull. Jpn. Soc. Mech. Eng., 17, No. 108, 768-775 (1974).
8. I. M. Razumov, Pneumatic and Hydraulic Transport in the Chemical Industry [in Russian], Khimiya, Moscow (1979).
9. G. A. Babukha and A. A. Shraiber, Interaction of Particles of a Polydisperse Material in Two-Phase Flows [in Russian], Naukova Dumka, Kiev (1972).
10. V. N. Milyutin and A. A. Shraiber, "Experimental study of the interaction of a gas-suspension flow with the walls of a vertical channel," Teor. Osn. Khim. Tekhnol., 10, No. 2, 239-247 (1976).
11. A. A. Shraiber and V. N. Milyutin, "Model of the motion of a disperse material in a vertical gas-suspension flow," Teor. Osn. Khim. Tekhnol., 13, No. 2, 212-217 (1979).
12. L. I. Krupnik, V. N. Oleinik, and V. G. Ainshtein, "Piezoelectric measurement of local characteristics of the motion of solid particles in a two-phase flow," Inzh.-Fiz. Zh., 40, No. 1, 101-108 (1981).
13. I. N. Taganov, O. A. Galkin, and P. G. Romankov, "Study of statistical characteristics of the motion of particles in a polydisperse fluidized bed," Teor. Osn. Khim. Tekhnol., 1, No. 6, 825-830 (1967).
14. G. N. Patterson, Molecular Gas Flows [Russian translation], Izd. Fiz.-Mat. Lit., Moscow (1960).
15. N. I. Gel'perin, V. G. Ainshtein, L. I. Krupnik, and Z. N. Memedlyaev, "Regimes of motion of a vertical gas-suspension flow," Tr. Mosk. Inst. Tonkoi Khim. Tekhnol., 5, No. 1, 134-136 (1975).