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EFFECT OF COARSE IMPURITY PARTICLES ON TURBULENT CHARACTERISTICS OF GAS SUSPENSIONS IN CHANNELS

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Turbulent flows of a gas with particles are realized in many pieces of energy production and chemical industry equipment. The wide range of size, concentration, and makeup of particles thus transported creates the need for a reliable method of predicting the turbulent characteristics of dispersed flows as a function of flow regime. Distortion of carrier phase flow parameters in the presence of a dispersed impurity determines the suspension capability of the flow, energy losses in pneumotransport systems, and the degree of channel wall erosion due to particle collision with the surface. The mechanism and intensity of the particles' effect on carrier phase parameters are related to the mass concentration of the impurity and the ratio of the particle dynamic relaxation time to the characteristic time scale for damping of energy capacity variations of the continuous phase. Chaotic motion of time particles, the dynamic relaxation times of which are less than or of the same order of magnitude as the time scale of pulsations in gas velocity produce a viscous resistance force caused by interphase pulsation slippage. In this case the change in flow pulsation characteristics is the result of the direct action of the foreign particles on the turbulent fine scale structure of the gas (see, for example, [1-3]). The difference between average characteristics of the dusty and single-phase flows is related to change in intensity of turbulent momentum transport of the carrier phase in the presence of particles.

For coarse particles, the dynamic relaxation times of which significantly exceed the time scale of turbulent fluctuations of the continuous phase, there is a qualitative change in the mechanism by which the discrete foreign substance affects the carrier flow. Due to the significant difference in time scales of particle and turbulent vortex motion there is little direct effect of particles on the intensity of gas velocity pulsations. Turbulent motion of the foreign material is caused by collisions of particles with the channel walls in which, on the hand, the particles lose part of their momentum upon inelastic collision upon the wall, while on the other, they take on an intense rotation about their own axis. The Magnus force developed as a result of this rotation is the case of intense chaotic mixing of the particles across the channel. The loss of momentum by particles upon collision with the surface leads to a significant average phase slippage [4-6]. The velocity of the discrete impurity is higher than the gas velocity near the wall and markedly lower within the core of the flow. Distortion of the average gas velocity profile is the result of the interphase aerodynamic resistance force. Change in the average velocity gradients of the continuous phase with shear exerts of significant effect on the level of gas velocity fluctuations. Aside from the mechanism of reverse action of coarse particle impurities on the flow discussed above, direct generation of small scale vortices due to flow detachment from particle surfaces [7] is also possible.

Direct stochastic modeling of the dynamics of turbulent flows with particles (see, for example, [8]), where the Lagrangians of particle trajectories are calculated in the field of random velocity fluctuations of the continuous phase excited by a stochastic source in the equation of motion for the latter phase yields unique information on the mechanism of foreign particle action on the structure of turbulent vortices. However this method of description is applicable only to flows with fine impurity particles at a low mass concentration. From the computation viewpoint it is more economical to use a model including integration of a set of particle trajectories, realized by including a random component in the gas velocity with a specified distribution law for its change in the particle dynamics equations [9]. The level of fluctuation motion of the liquid phase is calculated with turbulence models for a single-phase flow. Use of this method to study the reverse effect of flow structure of large size foreign particles randomly colliding with the walls may require significant expenditures of machine time.

A more realistic method for describing the hydrodynamics of a gas suspension with consideration of the effect of particles on carrier flow characteristics involves use of a system of balance equations for characteristics of the continuous and discrete phases, written in Euler representation. To realize such a program it is necessary to develop a technique for closing

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he system of balance equations and to write a system of boundary conditions representing the process of particle collision with he surface. The Euler method of modeling the flow of gaseous suspension of particles with consideration of particle rotation and collision with the walls first realized in [10]. Calculations were carried out on the basis of a system of equations for the irst and second moments of the fluctuations of velocity and the angular velocity of particle rotation. The Boussinesq gradient approximation was used to define the third order moments.

In [11] the present author proposed another method, different in principle, for describing the dynamics of coarse particles in channels, based upon an equation for the probability density of distributions over coordinates, velocities and angular rotation velocities of particles about their own axis. A closed system of equations was written for the first and second moments of velocity and particle rotation angular velocity. Expressions for the second and third moments, representing turbulent momentum transport, the moment of the momentum, and the intensity of fluctuation motion of the particles were found by approximate solution of the kinetic equation for the probability density with consideration of first order terms in gradients of the averaged dispersed phase parameters. Use of relationships for a single particle before and after collision, together with approximate solution of the kinetic equation, allows one to write boundary conditions (of third order) for the balance equations for the first second moments of particle characteristic fluctuations. Only data on the dynamics of an isolated particle are required to realize the system of equations.

In the present study the method of the probability density function for particle distributions over coordinates, velocities, and rotational angular velocities will be used to create a closed system of balance equations for the first and second moments of carrier gas velocity fluctuations with consideration of interphase interaction. Use of the probability density method permits proper completion of the equations for the second moments of continuous phase velocity pulsations and consideration of terms previously neglected in [10]. The equation for turbulent gas energy also includes a term which describes supplemental generation of fine-scale fluctuations produced by gas flow over particles at high Reynolds numbers, calculated using the relative phase slippage velocity and the particle diameter. Using a single-parameter approximation for modeling the turbulent gas flow with consideration of interphase interaction, we will study the mechanism of carrier phase turbulence suppression and generation in the presence of particles and calculate by hydraulic resistance for ascending and descending gas suspension flows in tubes. The calculation results will be compared to experimental data.

1. System of Equations for Average and Second Moments of Gas Velocity Fluctuations. We will consider the flow of a gas with low volume concentration of foreign particles without consideration of interparticle collisions. The system of equations describing the action of foreign particles on the continuous phase has the form

$$\frac{\partial U_i}{\partial t} + U_k \frac{\partial U_i}{\partial x_k} = -\frac{1}{\rho_1}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_k \partial x_k} - \frac{\rho_2}{\rho_1}\sum_{p=1}^{N} \frac{q_p}{Q_N}\delta(\mathbf{x} - \mathbf{R}_p(t))F_i(\mathbf{R}_p, t), \quad \frac{\partial U_i}{\partial x_i} = 0; \tag{1.1}$$

$$F_i(\mathbf{R}_p, t) = \frac{1}{\tau}(U_i(\mathbf{R}_p, t) - V_{pi}) - \gamma_\omega \epsilon_{ijk}\Omega_{pk}(U_j(\mathbf{R}_p, t) - V_{pj}), \tag{1.2}$$

where U_i, P are the gas velocity and pressure; V_{pi}, R_{pi}, Ω_{pi} are the velocity, coordinate and angular rotation velocity of particle p; F_i is the acceleration produced by interphase interaction; g_i is the acceleration due to mass forces; τ is the particle velocity dynamic relaxation time, in the general case dependent upon the relative velocity of flow over the particles and the particle angular rotation velocity; ν is the kinematic gas viscosity; ρ_1, ρ_2 are the densities of the gas and the particle material; γ_ω is a parameter proportional to the ratio of gas and particle densities and dependent on the relative overflow velocity and rotation intensity; $q_p = \pi d_p^3/6$ is the volume of particle p; Q_N is the flow volume containing N particles; $\delta(x)$ is the Dirac delta-function; e_{ijk} is an antisymmetric tensor.

The system of equations describing particle dynamics in the flow and the mechanism of particle collision with the walls is analogous to that of [11].

In order to transform from the Lagrangian description of Eq. (1.1) to an Eulerian one we introduce the probability density of particle distributions over coordinates, velocities, and rotational angular velocity:

$$\Phi_p(\mathbf{x}, \mathbf{V}, \Omega, t) = \delta(\mathbf{x} - \mathbf{R}_p)\delta(\mathbf{V} - \mathbf{V}_p)\delta(\Omega - \Omega_p). \tag{1.3}$$

The given model does not consider the effect of interparticle collisions, so that to describe the behavior of a set of independent particles it is sufficient to consider the probability density of an individual particle Φ_p.

To obtain data on the characteristics of the turbulent flow we average Eq. (1.1) and the equations for the second moments of gas velocity over the set of turbulent realizations. As we do this, there appear in the equations for averaged velocity and second moments of the continuous phase certain terms related to interphase interaction, expressed in terms of the probability density (1.3):

$$A_i = \int dV \int d\Omega \langle \Phi_p \left[\frac{U_i(x, t) - V_i}{\tau} - \gamma_\omega \varepsilon_{ijk} \Omega_k (U_j(x, t) - V_j) \right] \rangle; \tag{1.4}$$

$$B_{im} = \int dV \int d\Omega \langle \Phi_p \left[\frac{U_i(x, t) - V_i}{\tau} - \gamma_\omega \varepsilon_{ijk} \Omega_k (U_j(x, t) - V_j) \right] u_m(x, t) \rangle, \; U_i = \langle U_i \rangle + u_i. \tag{1.5}$$

Here the angle brackets denote results of averaging. To expand Eqs. (1.4), (1.5) we need an expression for the correlator $\langle \Phi_p u_m \rangle$ [11].

$$\langle \Phi_p u_m \rangle = -f \langle u_m u_l \rangle \frac{\partial \langle \Phi_p \rangle}{\partial V_l} - T_E \gamma_\omega \varepsilon_{kln} \langle u_m u_l \rangle \Omega_k \frac{\partial \langle \Phi_p \rangle}{\partial V_n}, \quad f = 1 - \exp(-T_E/\tau) \tag{1.6}$$

(where T_E is the characteristic time of energy fluctuations in the gas velocity).

Substituting Eq. (1.6) in Eqs. (1.4) and (1.5) we write equations for the averaged velocity and second single-point moments of gas velocity fluctuations in the presence of particles:

$$\frac{\partial \langle U_i \rangle}{\partial t} + \langle U_k \rangle \frac{\partial \langle U_i \rangle}{\partial x_k} + \frac{\partial}{\partial x_k} \left(\langle u_i u_k \rangle - \nu \frac{\partial \langle U_i \rangle}{\partial x_k} \right) = -\frac{1}{\rho_1} \frac{\partial \langle P \rangle}{\partial x_i} - \frac{\rho_2}{\rho_1} \langle C \rangle \left\{ \frac{\langle U_i \rangle - \langle V_i \rangle}{\tau} - \gamma_\omega \varepsilon_{ijk} [\langle \Omega_k \rangle (\langle U_j \rangle - \langle V_j \rangle) - \langle \omega_k v_j \rangle] \right\}; \tag{1.7}$$

$$\begin{gathered} \frac{\partial \langle u_i u_j \rangle}{\partial t} + \langle U_k \rangle \frac{\partial \langle u_i u_j \rangle}{\partial x_k} + \frac{\partial \langle u_i u_j u_k \rangle}{\partial x_k} + \langle u_i u_k \rangle \frac{\partial \langle U_j \rangle}{\partial x_k} + \langle u_j u_k \rangle \frac{\partial \langle U_i \rangle}{\partial x_k} = \\ -\frac{1}{\rho_1} \left(\frac{\partial \langle u_i p \rangle}{\partial x_j} + \frac{\partial \langle u_j p \rangle}{\partial x_i} \right) + \frac{1}{\rho_1} \langle p \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \rangle + \\ \nu \frac{\partial^2 \langle u_i u_j \rangle}{\partial x_k \partial x_k} - 2\nu \langle \frac{\partial u_i}{\partial x_k} \frac{\partial u_j}{\partial x_k} \rangle - \\ \frac{\rho_2}{\rho_1} \langle C \rangle (B_{ij} + B_{ji}) + \langle C \rangle G_{ij}, \\ B_{ij} = \frac{1}{\tau} \langle u_i u_j \rangle (1 - f) + \gamma_\omega \varepsilon_{kni} \langle \Omega_k \rangle \langle u_n u_j \rangle - \\ 2T_E/\tau \gamma_\omega \varepsilon_{kli} \langle u_j u_l \rangle \langle \Omega_k \rangle - T_E \gamma_\omega^2 \varepsilon_{kin} \varepsilon_{pln} \times \\ \langle u_j u_l \rangle (\langle \Omega_k \rangle \langle \Omega_p \rangle + \langle \omega_k \omega_p \rangle), \\ \langle N \rangle = \int dV \int d\Omega \langle \Phi \rangle, \; \langle V_i \rangle \langle N \rangle = \int dV \int d\Omega V_i \langle \Phi \rangle, \\ \langle \Omega_i \rangle \langle N \rangle = \int dV \int \partial \Omega \Omega_i \langle \Phi \rangle, \; \langle \Phi \rangle = \sum_{p=1}^{N} \langle \Phi_p \rangle, \\ \langle C \rangle = \langle N \rangle q_p / Q_N, \; v_i = V_i - \langle V_i \rangle, \; \omega_i = \Omega_i - \langle \Omega_i \rangle. \end{gathered} \tag{1.8}$$

Here $\langle N \rangle$, $\langle C \rangle$ are the numerical and volume particle concentrations in the flow; $\langle V_i \rangle$, $\langle \Omega_i \rangle$, u_i, ω_i are the averaged and pulsation components of velocity and particle angular velocity. The terms in the expression for B_{ij} are additional dissipation of the intensity of carrier phase fluctuation motion due to pulsation phase slippage, caused by both viscous resistance to particle transnational motion as well as the Magnus force.

The term G_{ij} on the right side of Eq. (1.8) reflects additional generation of fine-scale fluctuations in the gas, produced by flow over particles. To described the mechanism underlying this effect of the impurity on turbulence of the fluid phase we assume that the intensity of gas pulsation generation due to flow over an isolated particle is proportional to the work done by the component of the viscous resistance force related to the non-Stokesian nature of the overflow over the relative displacement of the particle per unit time. In that case the expression for G_{ij} takes on the form

$$
\begin{gathered}
G_{ij} = \delta_{ij}\beta_g(3/4)C_D'|U - V|^3/d_p(1 - \exp(-\mathrm{Re}_p/\mathrm{Re}_{pc})), \\
C_D = 24/\mathrm{Re}_p + C_D', \ \mathrm{Re}_p = d_p|U - V|/\nu,
\end{gathered}
\tag{1.9}
$$

where Re_p is the Reynolds number for flow over the particle; C_D is the total aerodynamic resistance coefficient of a spherical particle; C_D' is the aerodynamic resistance component considering the non-Stokesian nature of the overflow; Re_{pc} is the characteristic Reynolds number for flow over particles, beginning at which detachment of vortices from the particle surface occurs; β_g is an empirical constant.

The system of equations (1.7)-(1.9) together with the balance equations for concentration, averaged velocity, and rotational angular velocity, second moments of particle velocity fluctuation, and the boundary conditions considering particle collisions with the channel walls [11] permit modeling of a gas flow with a large particle impurity, with consideration of the reverse effect of the dispersed component on characteristics of the carrier phase.

2. Calculation Results. We will consider a flow in the stabilized portion of a circular vertical tube. The characteristics of turbulent flow of the continuous medium with particles will be considered within a single-parameter turbulence model. The equations for average flow velocity and gas pulsation energy have the form

$$
\begin{gathered}
\frac{1}{(1 - y')}\frac{d}{dy'}\left[(1 - y')\frac{1}{\mathrm{Re}}(1 + \nu_t')\frac{dU_x'}{dy'}\right] - \\
\frac{1}{2}\frac{\rho_2}{\rho_1}\langle C\rangle\frac{U'}{\mathrm{St}} = -K - \frac{1}{2}\frac{\rho_2}{\rho_1}\langle C\rangle\left[\frac{V_x'}{\mathrm{St}} - \gamma_\omega(\Omega' V_y' + \langle\omega' v_y'\rangle)\right];
\end{gathered}
\tag{2.1}
$$

$$
\begin{gathered}
\frac{1}{(1 - y')}\frac{d}{dy'}\left[(1 - y')\left(\frac{1}{\mathrm{Re}} + c_1\mathrm{Re}_t\right)\frac{de'}{dy'}\right] - \frac{c_2}{2}\frac{e'^{3/2}}{L'} - \frac{c_3}{\mathrm{Re}}\frac{e'}{L'^2} - \\
\frac{\rho_2}{\rho_1}\langle C\rangle\left[\frac{1}{\mathrm{St}}\exp\left(-\frac{T'}{\mathrm{St}}\right) - \gamma_\omega bT'(\Omega'^2 + \langle\omega'^2\rangle)\right]e' = -\frac{\nu_t'}{\mathrm{Re}}\left(\frac{dU'}{dy'}\right)^2 - \langle C\rangle G', \\
\langle\omega' v_y'\rangle = -(1 + \tau/\tau_\omega)^{-1}\mathrm{St}\sigma_{yy}'\partial\Omega'/\partial y', \\
\langle\omega'^2\rangle = \tau/\tau_\omega(1 + \tau/\tau_\omega)^{-1}\mathrm{St}^2\sigma_{yy}'(\partial\Omega'/\partial y')^2, \\
G' = (9/8)\beta_g C_D'|U_x' - V_x'|^3/d'(1 - \exp(-\mathrm{Re}_p/\mathrm{Re}_{pc})), \\
T' = T_E U_m/R, \ \nu_t' = c_4\mathrm{Re}_t^2/(c_5 + \mathrm{Re}_t), \\
K = -R/(2\rho_1 U_m^2)\partial\langle P\rangle/\partial x,
\end{gathered}
\tag{2.2}
$$

where $\mathrm{St} = \tau U_m/R$ is the particle Stokes number; U_m is the mean-mass flow velocity; R is the channel radius; $\mathrm{Re} = 2RU_m/v$ is the flow Reynolds number; $e' = 0.5<u_iu_i>/U^2$ is the dimensionless turbulent energy of the gas; $\Omega' = \Omega R/U_m$ is the dimensionless turbulent energy of the gas; $\omega' = \omega R/U_m$ is the dimensionless angular velocity of a particle's rotation about its own axis; $\omega' = \omega R/U_m$ is the dimensionless fluctuation of the particle angular rotation velocity $\sigma_{ij}' = <v_iv_j>/U_m^2$; $V_i' = <V_i>/U_m$ is the dimensionless mean particle velocity; $L' = L_E/R$ is the dimensionless scale factor for Nikuradze displacement; $\mathrm{Re}_t = L'e'^{1/2}$ is the turbulence Reynolds number; the value of the constant b in Eq. (2.2) is chosen from the condition $e_{xx}' + e_{yy}' = be$. The intensities of longitudinal and transverse gas velocity fluctuations are taken proportional to the turbulent energy $e_{xx}' = \varkappa_x e'$, $e_{yy}' = \varkappa_y e$ ($\varkappa_x = 1.17$, $\varkappa_y = 0.25$). The characteristic time for energy-bearing gas velocity pulsations was evaluated as in [11]. Values of the constants c_1, c_2, c_3, c_4, c_5 were selected equal to the corresponding values for the case of single-phase turbulence in [2], while the constant β_g in the expression for gas velocity pulsation generation due to detachment of vortices was taken equal to 0.25, $\mathrm{Re}_{pc} = 40$.

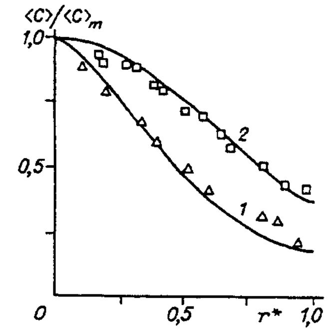


Fig. 1

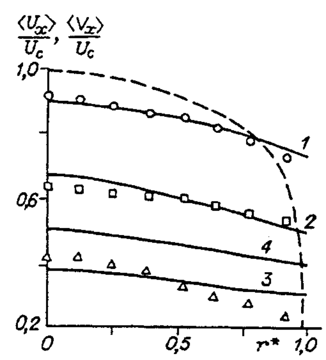
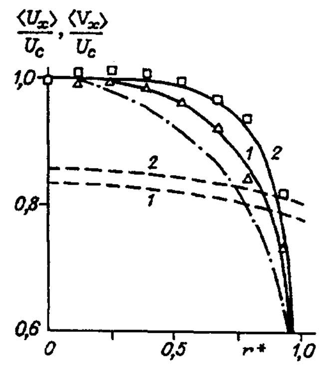


Fig. 2



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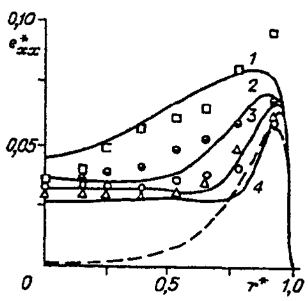

Fig. 4

The boundary conditions for the gas dynamics equations follow from the attachment and symmetry conditions y' = 0.

$$U'_x = e' = 0;\ y' = 1:\ \partial U'_x/\partial y' = \partial e'/\partial y' = 0. \tag{2.3}$$

Simultaneous solution of the system (2.1)-(2.3) was carried out numerically by iteration methods to the pre-specified calculation accuracy. The scale factor of discrete phase characteristics significantly exceeds the scale of gas characteristics over the section. In connection with this, the calculations of particle and gas dynamics were performed in independent grids. The particle parameters were determined by a purely implicit method of construction on an almost uniform grid, with the gas flow characteristics being approximated by cubic splines. Iterative calculation of the carrier phase flow was realized on a non-uniform grid, more dense near the tube walls. In this case the discrete phase parameters were approximated by cubic splines.

The parameter K in Eq. (2.1), representing the flow hydraulic resistance, was calculated by applying a branching procedure to Eq. (2.1), based on relationships obtained from Eq. (2.1) by integrating over the channel section:

$$K = \frac{2}{\mathrm{Re}}\frac{dU'}{dy'}\Big|_{y'=0} + \frac{1}{2}\frac{\rho_2}{\rho_1}\left\{\frac{1}{\mathrm{St}}\left[(\langle C\rangle U'_x)_m - (\langle C\rangle V'_x)_m\right] + \gamma_\omega\left[(\langle C\rangle\Omega' V'_y)_m + (\langle C\rangle\langle\omega' v'_y\rangle)_m\right]\right\}. \tag{2.4}$$

Here the index m denotes mean-values.

The profiles of mean discrete coarse particle phase characteristics are generated by interaction of particles with the channel walls. In particular, a bell-shaped particle concentration profile is realized under the action of the magnus force produced by particle rotation after collision with the walls. Figure 1 shows a spherical particle distribution in a tube with 2R = 16 mm for a flow velocity of 30 m/sec (curve 1, bronze particles with d_p = 45 μm, $k_n = k_t$ = 0.6; curve 2, electrocorundum particles, d_p = 55 μm, k_n = 0.2, k_t = 0.6; points, experimental data [12]). Loss of particle momentum upon collision with the walls produces an intense average phase slippage. In Fig. 2 calculations of average slippage are compared with experimental data [13] (tube diameter 2R = 30.5 mm, $k_n = k_t$ = 0.6, U_c is the gas velocity on the tube axis, curve 1, particles with d_p = 200 μm, Re = $3.3\cdot10^4$, 2, d_p = 500 μm, Re = $1.6\cdot10^4$, 3, d_p = 3000 μm, Re = $3.1\cdot10^4$, 4, d_p = 1000

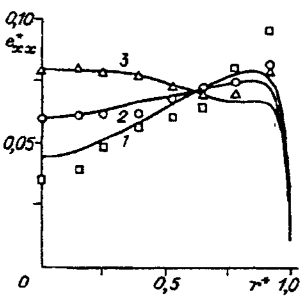

Fig. 5

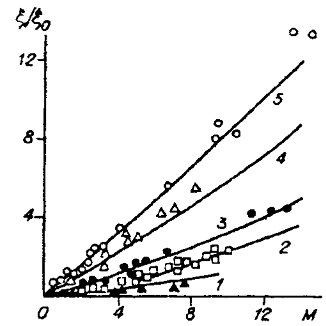

Fig. 6

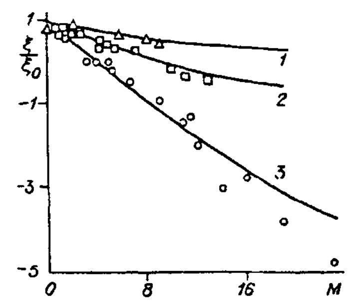

Fig. 7

μm, Re = $1.6 \cdot 10^4$; dashed line, gas velocity). The bell-shaped particle concentration profile and uniform particle velocity distribution over channel section causes the maximum interphase interaction to be concentrated in the flow core. There is then a significant distortion of the average gas velocity profile. Figure 3 shows gas and particle velocity profiles in accordance with the experimental data of [13] (dash-dot line, gas velocity in absence of particles, dashes, particle velocity; solid lines, gas velocity with d_p = 200 μm particles; curves 1 for impurity mass flow concentration 2 kg/kg; 2, 3.2 kg/kg). It is evident from Fig. 3 that the degree of carrier phase velocity distortion increases with increase in impurity concentration. With growth in concentration the particle velocity increases, which corresponds to the experiments of [13]. Reduction in the gradients of average carrier phase velocity in the flow core leads to decrease in the intensity of gas velocity fluctuation generation. This effect is shown clearly in Fig. 4, where comparison is presented with experimental data of [13] for the intensity of longitudinal gas velocity fluctuations for the case of a flow of particles with $d_p \pm 200$ μm, Re = $2.3 \cdot 10^4$ (curves 1-4 correspond to flow concentrations 0, 1, 1.9, 3.2, while the dashed line is the result of calculations without consideration of additional gas velocity fluctuation generation due to detachment of vortices from the surfaces of particles flowed over). The effect of the inertial particle impurity upon continuous phase turbulence is caused, on the one hand, by reduction in the level of gas velocity pulsation generation in the flow volume, and on the other, by direct generation of velocity pulsations by flow over particles at high particle Reynolds numbers ($Re_p >> 1$). The effect of additional generation of fine scale motion in the carrier phase is manifested clearly in the presence of relatively large impurity particles with marked average phase slippage. Figure 5 compares calculations for intensity of longitudinal gas fluctuations with experimental data of [13], obtained for a gas flow with Re = $2.3 \cdot 10^4$ and d_p = 1000 μm (curves 1-3 represent mass flow concentrations of 0, 1, 3).

As follows from Eq. (2.4), in transport of a gas suspension in tubes, as compared to flow of a single phase, a significant contribution to hydraulic resistance is produced by the interphase resistance force. Since interphase velocity slippage is generated by the force of gravity acting on particles and particle momentum loss upon collision with the walls, these effects are considered implicitly in calculating the parameter K of Eq. (2.1), which is proportional to the hydraulic resistance coefficient of the dusty flow.

Figure 6 shows a comparison of calculated and experimental [14] ratios of hydraulic resistance of the pure gas ξ_0 and the suspension ξ as a function of mass flow concentration of coal particles with d_p = 230 μm in an ascending flow in a vertical tube 16 mm in diameter (curves 1-5 correspond to flow Reynolds numbers of $32 \cdot 10^3$, $19 \cdot 10^3$, $11.6 \cdot 10^3$, $7.6 \cdot 10^3$, $6.5 \cdot 10^3$). As follows from Fig. 6, with reduction in flow velocity carrier phase, energy losses to work performed against gravity increase. In the case of a descending flow, particle motion in the gravitational field may lead to increase in pressure drop over the course of the flow. Figure 7 shows theoretical and experimental data on hydraulic resistance for a descending flow [14]. Calculations were performed for a suspension of the same type as in Fig. 6, with the exception of flow direction (curves 1-3 correspond to flow Reynolds numbers $20 \cdot 10^3$, $11.5 \cdot 10^3$, $6.3 \cdot 10^3$).

Thus, a probability method has been presented for description of turbulent flow of a gaseous suspension of relatively large particles, based on use of the apparatus of the probability density function for particle distribution over their characteristics. The method presented allows construction of complete models for calculation of complex two-phase flows of gases with particles, which are of practical importance.

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