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WALL–PARTICLE INTERACTION IN A VERTICAL GAS SUSPENSION FLOW

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The results of an experimental investigation of the carrier velocity fields in a vertical gas suspension flow are presented, and the development of the shear stress due to interaction between the particles and the channel walls is analyzed.

A quantitative evaluation of the relation between the velocity distribution in a developed turbulent continuum flow and the tangential wall stress (τ_g), based on the Prandtl mixing length hypothesis, leads to the logarithmic law:

$$\frac{w}{w_*^g} = A_0 \lg \frac{w_*^g y}{\nu} + B_0. \qquad (1)$$

With respect to gas suspension flows, on the interval $30 \leq w_*^g y/\nu \leq 700$ this law quite satisfactorily describes [1-3] the velocity field of the carrier medium [at various mean velocities $w_m = 8$–30 m/sec and solids flow concentrations $\mu_f = 0.1$–16 $(\text{kg}\cdot\text{h}^{-1})/(\text{kg}\cdot\text{h}^{-1})$] as deformed by the presence of the solid particles.

Investigations were carried out [2, 3] by means of a Pitot tube in channel sections of diameter D = 2R = 50 mm with various degrees of hydrodynamic flow stabilization L/D = 11-111. In the experiments we used narrow fractions of quartz sand of diameter d = 0.17 mm, AV-17 anion-exchange resin d = 0.52 mm, glass pellets d = 1.3 mm, corundum pellets d = 1.05 mm, and wheat d = 3.9 mm. Values of $\tau_g(w_*^g)$ were obtained from the data of measurements of the local carrier velocities w(y), using Clauser's method of nets [1] and Preston's equation [2]. In Fig. 1 we present the results of an investigation of the carrier velocity fields on the stabilized section (L/D = 100) of a vertical gas suspension flow. Clearly, in the inner region of the turbulent flow core all the experimental data (Fig. 1a) are grouped about dependence (1) with constants A_0 and B_0 equal to 5.5 and 5.8, respectively. It is noteworthy that, according to Nikuradze's data [4], the values $A_0 = 5.5$ and $B_0 = 5.8$ most accurately describe the experimental points in the turbulent wall region ($y/R \approx 0.2$) of continuum flows.

Attempts have been made to use an equation of type (1) to calculate the total resistance of a gas suspension flow (τ_t, ΔP_t) including, in addition to the carrier friction losses (τ_g, ΔP_g), the energy expended on keeping the particles in the suspended state (τ_s, ΔP_s) and the losses (τ_w, ΔP_w) due to interaction between the particles and the channel walls (friction, collision).† For this purpose the gas suspension is treated [5, 6] as a quasihomogeneous

†The introduction of the "tangential" stresses τ_s, τ_w and the corresponding dynamic flow velocities is justified only phenomenologically and constitutes a convenient mathematical technique.

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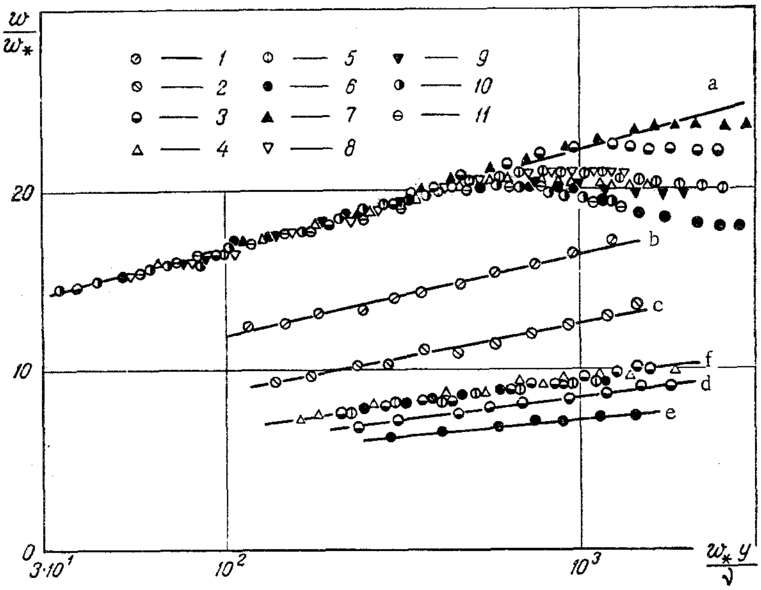

Fig. 1. Logarithmic carrier velocity profile in a vertical gas suspension flow: a) the dependence $w/w_*^g = f(w_*^g y/\nu)$; b-e) $w/w_*^f = f(w_*^f y/\nu)$; f) $w/w_*^{gw} = f(w_*^{gw} y/\nu)$. Corundum (d = 1.05 mm): 1) $\mu_f = 0.38$ $(kg\cdot h^{-1})/(kg\cdot h^{-1})$, w_m = ?5.9 m/sec; 2) 1.21 and 24.9; 3) 4.57 and 25.7; 4) 5.35 and 17.6; 5) 9.11 and 24.2; 6) 13.3 and 24.3. Glass (d = 1.30 mm): 7) μ_f = 5.76, w_m = 28.8; 8) 6.31 and 14.7; 9) 13.7 and 18.9. Anion-exchange resin (d = 0.52 mm): 10) μ_f = 3.15 and w_m = 14.4. Sand (d = 0.17 mm): 11) μ_f = 3.35 and w_m = 15.1.

flow with a uniform distribution of the solid phase over the channel cross section. Assuming that the mass velocities of the carrier medium and the solids make equal contributions to the eddy viscosity of the flow and calculating the dynamic velocity w_*^f from the measured total resistance ΔP_t, we obtain a "generalized" velocity field described by an equation of type (1). However, in this case the parameters A and B depend on the flow concentration μ_f and the particle diameter d.

Going over from this idealized model to the real motion of a gas suspension with deformed velocity fields and calculating w_*^f from the experimental values of ΔP_t also leads to a family of logarithmic lines (Fig. 1, lines b-e) with different numerical values of the parameters A and B, which depend, for a given type of granular material, on the quantity μ_f and to a lesser extent on w_m. It may be assumed that the stratification of the experimental points depending on the values of μ_f and w_m is due to the difference in the value of the component $\Delta P_s(\tau_s)$, methods of estimating which for vertical gas suspension flows are known.

The introduction of the dynamic velocity $w_*^{gw} = \sqrt{(\tau_g + \tau_w)/\rho}$, calculated from the sum of the shear stresses $\tau_g + \tau_w$ (in the absence of experimental values of τ_w this sum was found as the difference $\tau_f - \tau_s$), leads at $\mu_f \geq \mu_f'$ (see below) to the logarithmic profile

$$\frac{w}{w_*^{gw}} = A \lg \frac{w_*^{gw} y}{\nu} + B \tag{2}$$

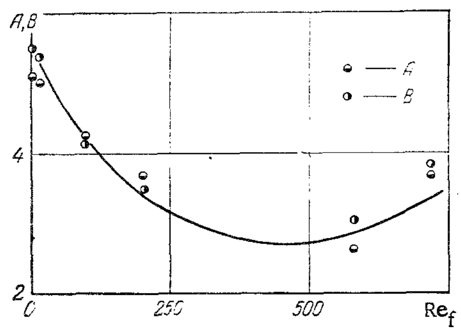

Fig. 2. Dependence of the constants A and B on $Re_f = w_{f1} d/\nu$.

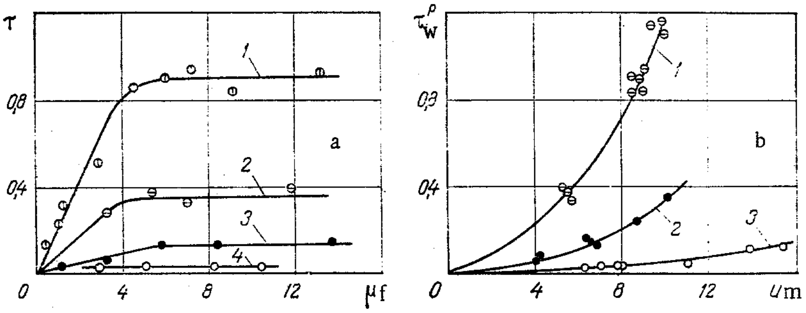

Fig. 3. Shear stress in a gas suspension flow as a function of flow concentration and particle velocity: a) $\tau_w = f(\mu_f)$; 1) corundum, w_m = 23.2-26.2 m/sec; 2) corundum, 17.0-18.0; 3) glass, 18.9-20.2; 4) anion-exchange resin, 8.9-10.8; b) $\tau_w = f(u_m)$: 1) corundum; 2) glass; 3) anion-exchange resin. τ_w, kg/m^2; μ_f, (kg·h^{-1})/(kg·h^{-1}); u_m, m/sec.

with constants A and B fixed for a given material irrespective of the flow parameters μ_f and w_m (Fig. 1, line f). The deviation of any straight line (2) from the generalized profile given by Eq. (1) is a measure of the shear stress τ_w and the corresponding dynamic velocity w_*^w.

The relations between A and B and the Reynolds number based on the particle entrainment velocity w_{f1} and the particle size d are presented in Fig. 2. In order to account for the extremal nature of the A—Re_f and B—Re_f curves, it is necessary to analyze the motion of the particles in the gas suspension flow and their interaction with the walls.

The effect of the principal factors on τ_w are indicated in Fig. 3. It is clear (Fig. 3a) that as the flow concentration increases to a certain critical value μ_f' [under the experimental conditions μ_f' does not exceed 3-4 (kg·h^{-1})/(kg·h^{-1}) and depends importantly on Re_f and w_m] the stress τ_w increases to the equilibrium value τ_w^e, after which it remains unchanged. In this case higher values of the mean carrier velocity correspond to higher equilibrium stresses. The relations between τ_w^e and the mean particle velocity are presented in Fig. 3b. The observed effects are consistent with the data of direct measurements of the number of wall—particle collisions for various granular materials as a function of flow concentration and mean flow velocity [7]. These facts can be explained in terms of a disperse core flow regime, the formation of which is complete once the flow concentration μ_f' reaches very low critical values. Beyond the latter the disperse core flow regime is stable: the particles move primarily in the flow core and their transport is characterized by constancy of the momentum exchange with the channel walls.

According to the data of the authors of [7], the number of particle—wall collisions is greater for particles with small Re_f values, since light particles have a greater tendency to radial motions, following the turbulent pulsations of the gas flow. On the other hand, heavy particles, characterized by high Re_f values, tend by inertia to move along straight-line trajectories (i.e., the number of collisions with the channel walls and hence the value of τ_w are reduced). This, however, does not mean that a decrease in Re_f is accompanied by a continuous increase in τ_w. In fact, τ_w depends on the rate of momentum exchange, i.e., not only on the frequency (and velocity) of the particle—wall collisions, but also on the particle mass, and the latter is small for particles with small Re_f. The appearance of a maximum of τ_w at certain values of Re_f would appear to be attributable to precisely this simultaneous action of opposing tendencies; this maximum corresponds to a minimum on the A, B = f(Re_f) curve in the neighborhood of $Re_f \approx 500$. It is interesting to note that the value of Re_f associated with the maximum of τ_w corresponds to the conditions of transition to turbulent carrier flow over the particles.

It is possible that as τ_f increases degeneration of the disperse core flow regime may be observed. In this case the constant of $\tau_w = \tau_w^e$ may be expected to be disturbed.

NOTATION

w, w_m, local and mean gas velocity in gas suspension flow; u_m, mean particle velocity; τ_g, ΔP_g, shear stress and pressure drop in gas suspension flow due to gas friction against the channel walls; τ_w, ΔP_w, shear stress and pressure drop in gas suspension flow due to interaction of the particles with the channel walls; τ_s, ΔP_s, shear stress and pressure drop due to weight of particles; τ_f, ΔP_f, shear stress and pressure drop in gas suspension flow; τ_w^e, equilibrium value of shear stress τ_w; w_*^g, w_*^w, w_*^s, w_*^f dynamic velocities calculated from τ_g, τ_w, τ_s, τ_f, respectively; A_0, B_0, parameters of the "law of the wall"; $\mu_f{}'$, flow concentration corresponding to minimum of τ_w^e; ν, ρ, kinematic viscosity and density of carrier medium; d, particle diameter; w_{fl}, particle entrainment velocity; $Re_f = w_{fl}d/\nu$, Reynolds number; y, distance from wall.

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THEORY OF CENTRIFUGAL SEDIMENTATION OF LARGE PARTICLES

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The motion of particles of finite size in rotating viscous liquids is investigated. On the basis of the properties of centrifugal sedimentation described, its possible technical applications are discussed.

In modern science and engineering, centrifugal sedimentation of suspensions containing solid particles of greatly differing sizes is widely used. However, the theory of the motion of particles in a rotating viscous liquid has been developed mainly for fairly small particles [1-4]. The present paper examines the motion of particles of arbitrary size. The results obtained suggest possible new technical applications of the centrifugal sedimentation of suspensions.

Consider the motion of particles of a Stokes diameter a, mass m, and density ρ in a liquid (viscosity η, density ρ_0) rotating at angular velocity ω. The equations of motion of the particles in a coordinate system rigidly fixed in a liquid rotating in a vertical plane are [4]

$$\begin{aligned} c\ddot{x} &= sx - b\dot{x} - k\dot{y} + n\sin\omega t, \\ c\ddot{y} &= sy - b\dot{y} + k\dot{x} - n\cos\omega t, \end{aligned} \qquad (1)$$

where

$$s = a^2(\rho - \rho_0)\omega^2,\ b = 18\eta,\ k = 2a^2\rho\omega,$$
$$c = a^2\rho,\ n = a^2(\rho - \rho_0)g.$$

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