ENERGY LOSSES IN A TWO-PHASE FLOW AT INTERACTION OF SOLID PARTICLES WITH THE WALL OF A VERTICAL CHANNEL

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UDC 532.529.5

Experimental and calculated data on the interaction of solid particles with the wall of a conveying pipe are presented.

Analysis of the current status of the hydrodynamics of gas-solid particle flows which are widely practiced in many branches of engineering shows the absence of physically substantiated methods for calculating hydraulic resistance of this system. Attempts at formally employing the mechanisms of continuum flow, for instance, in the form of the Fanning equation [1, 2], to correct for the pressure loss component due to the interaction of particles between themselves and with the channel walls are lacking a physical sense. As a consequence, calculating the coefficient of resistance by numerous empirical expressions leads to numerical values of energy losses with a difference of several times under similar conditions.

More justified is a method based on invoking the parameters of particle interaction with the channel walls [3, 4]. As is shown in [3], hydraulic resistance can be expressed by the dependence on the frequency of particle collisions with the channel wall and by a variation in its velocity in the process of collision:

$$\Delta P_{\mathrm{dr}} = \frac{2}{3}\rho\frac{L}{D} f\pi d^3\Delta u_x. \tag{1}$$

The quantity Δu_x in Eq. (1) is a function of the restoration factor of the tangential component of particle velocity [3, 5-9], which as shown in the work [10] depends on such quantities as the coefficient of sliding friction, the restoration factor of the normal velocity component, the angle of attack, and the angular rotation velocity of particles at the instant they collide, the determination of each being a difficult experimental problem.

The present work has been performed on the basis of the notion of kinetic energy dissipation of particles at their inelastic collisions, developed in [11] by analyzing experimental functions of particle velocity distribution.

In particular, it was shown that in a two-phase flow, as a result of a random particle motion, dynamic equilibrium is established in which dissipation of the colliding particle kinetic energy is compensated by the carrier gas flow energy. In other words, the work done by the gas flow over the time Δt to restore the velocity of particles u upon their interaction with the channel wall to an equilibrium value of $\bar{u}$ can be expressed by the equation

$$\Delta P_{\mathrm{dr}}\frac{\pi D^2}{4}\bar{u}\Delta t = \Delta E\Delta t. \tag{2}$$

We will present the dissipation ΔE of kinetic energy of particles at collision with the wall in a channel with diameter D and length L as [12]:

$$\Delta E = \pi DLf\frac{m\bar{u}^2}{2}(1 - n^2). \tag{3}$$

State Research and Design Institute of Chemical Technologies, Severodonetsk, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 63, No. 3, pp. 333-338, September, 1992. Original article submitted April 9, 1991.

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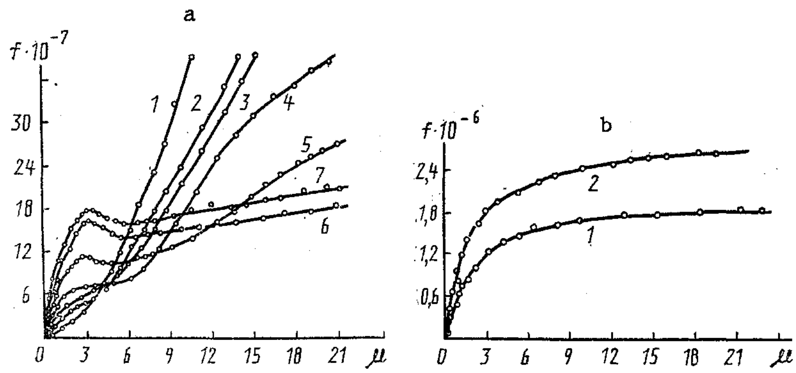

Fig. 1. Dependence of the density of collisions f against the channel wall on the mass flow-rate concentration μ: a) for particles 0.113 mm in diameter: 1) ω = 4.78 m/sec; 2) 7.4; 3) 9.8; 4) 12.3; 5) 15; 6) 17.4; 7) 23.1; b) for particles 1.18 mm in diameter: 1) ω = 16.5 m/sec; 2) 23.5. $f \cdot 10^{-6}$, $f \cdot 10^{-7}$ $1/(m^2 \cdot sec)$.

The total velocity of a particle at the instant it collides, with isotropy of transverse velocities allowed for, can be presented in the following manner:

$$\bar{u} = \sqrt{\bar{u}_x^2 + 2\bar{u}_y^2}. \tag{4}$$

From Eq. (2) in view of (3) we obtain

$$\Delta P_{dr} = \frac{1}{3}\frac{L}{D}\pi d^3 f \rho_s (1 - n^2)\sqrt{\bar{u}_x^2 + 2\bar{u}_y^2}\,. \tag{5}$$

Thus, the parameters determining the value of the particle–wall interaction losses ΔP_{dr} are the frequency of particle collisions with the wall f and the restoration factor of the total particle velocity n.

The investigation of parameters of particle motion is performed on the stabilized section of a vertical pipe with the diameter D = 50 mm. The experiments are carried out in flows with spherical particle diameters of 1.18 and 0.113 mm and densities of 2699 and 6800 kg/m^3, respectively. The procedure for determining the values of f, $\bar{u}_x$, and $\bar{u}_y$ is given in detail in the works [13-15].

The collision density of particles for hydrodynamically large particles (d > 0.1 mm) was investigated in several works [7, 8, 16]. Practice of measurements of f using contact pickups has shown [6] that during the experiments there emerges an uncertainty in completeness of recording of collisions by the measuring circuit. In this connection it is pertinent to note that a device for pulse-amplitude analysis, which reflects the signal spectrum (equivalent to the radial velocity spectrum) on the oscillograph screen incorporated into the recording circuit, excludes any uncertainties. Such a construction of a measuring complex makes it possible to set the necessary circuit gain factor, ensuring a no-blank recording of collisions during a visual examination of trial histograms before each measurement.

A comparison of the dependencies f = f(μ) obtained in the works [7, 8, 16] with those presented in Fig. 1 shows that the present work has identified new features in the character of the solid phase–wall interaction. Thus, for glass particles (an average diameter is 113 μm) conveyed in a cylindrical channel it is found that, beside the known particle motion regime characterized by a decrease in the collision gain rate f as the flow-rate concentration μ increases [7, 8] at high velocities of a carrier medium (ω > 10v), there exists a regime with growing df/dμ from μ, observed at low velocities of the carrier medium (ω < 7v): curves 1-3 in Fig. 1a. It is essential that it is in these regimes that the collapse phenomenon is observed at the flow-rate concentrations μ > 10.

The statistically averaged velocity of the longitudinal $\bar{u}_{0x}(r)$ and radial; $\bar{u}_{0y}(r)$ travel of the solid phase is obtained from the results of measurements of local instantaneous velocities $u_x(r)$ and $u_y(r)$ for single particles [14, 15].

Figure 2 presents the characteristic functions of distribution of the longitudinal $P(u_x)$ (Fig. 2a-d) and radial $P(u_y)$ (Fig. 2e,f) velocities of particles with an average diameter of 113 μm. For particles 1.18 μm in diameter the similar functions were given earlier [14]. The functions $P(u_x)$ with a distribution close to the normal law (Fig. 2a, b) correspond to regimes with a steady motion of the solid phase (in Fig. 1a, curves 5-7 correspond to this regime as well as curves 1-3 for μ < 5-7; in Fig. 1b –

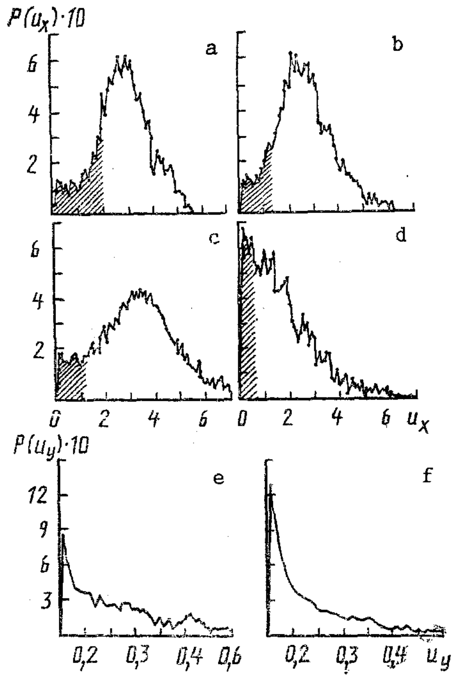

Fig. 2

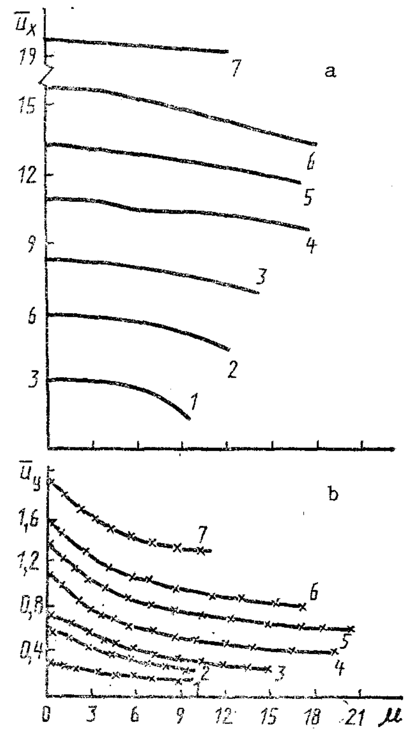

Fig. 3

Fig. 2. Functions of distribution of the longitudinal $P(u_x)$ and transverse $P(u_y)$ velocities of particles 0.113 mm in diameter at the gas velocity ω = 4.78 m/sec: a-d) $P(u_x)$; e,f) $P(u_y)$; a, b) μ = 2.68; c, d) 7.44; e) μ = 6.4; a, c) R = 0; b, d) 24 m. u_x, u_y, m/sec.

Fig. 3. Dependence of the velocity $\bar{u}_x$ and $\bar{u}_y$, averaged over the pipe cross section, for particles 0.113 mm in diameter on the mass flow-rate concentration μ: a) $\bar{u}_x$; b) $\bar{u}_y$; 1) ω = 4.78 m/sec; 2) 7.4; 3) 9.8; 4) 12.3; 5) 15; 6) 17.4; 7) 23.1.

curves 1, 2). Transition to the motion with a periodically occurring collapse of material (curves 1-3 in Fig. 1a for μ > 8-10) and a subsequent pistonlike ascending removal of particles is accompanied by the "deformation" function $P(u_x)$: as this process starts it is the functions $P(u_x)$ taken in the vicinity of the wall (Fig. 2d) and later the functions taken in the flow core that acquire the exponential form.

The functions $P(u_y)$ were basically taken with the pickup mounted on the wall since the preliminary measurements had shown insignificant variations in the radial velocities spectra across the channel cross section [15].

All the curves $P(u_y)$ (Fig. 2e, f) have a distinct positive asymmetry. In contrast to $P(u_y)$ for large particles (d = 1.18 mm) [14, 17], the functions for fine (d = 113 μm) ones have a practically exponential form, i.e., there is a noticeable fraction of particles moving with regard to the wall with zero angles of attack.

When employing local $P(u_x)$ and $P(u_y)$ functions, first we obtained the profiles of statistically averaged velocities u_{0x} and u_{0y} and then those of $\bar{u}_x$ and $\bar{u}_y$:

$$u_{0x,0y}(r) = \int\limits_0^\infty u_{x,y} P(u_{x,y})\, du_{x,y}, \tag{6}$$

$$\bar{u}_{x,y} = \frac{1}{R^2} \int\limits_0^R u_{x,y}(r)\, 2r dr. \tag{7}$$

Figure 3a presents the velocities $\bar{u}_x$ for fine particles with d = 113 μm (for large ones d = 1.18 mm [14]). Similar dependencies obtained under analogous conditions by a cut-off method permitted the authors [18] to obtain criterial equations for $\bar{u}_x$, calculation by which yields fairly close values to those obtained in the given work.

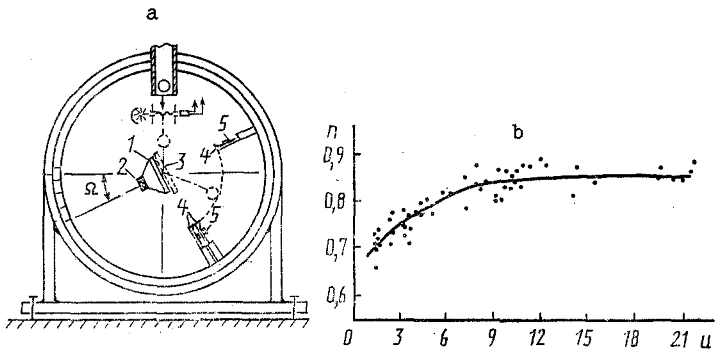

Fig. 4. Device for determination of the total velocity restoration factor (a) [1) contact plane; 2, 5) piezotransducers; 3) photo-transducer; 4) acoustic plate] and the total velocity factor vs upflight particle velocity (b). u, m/sec.

TABLE 1. Pressure Losses $\Delta P_{dr}/\Delta P_0$, %, Caused by Particle Collisions against the Channel Wall at Different Flow-Rate Concentrations

d, mm	w, m/sec	μ								
		1	2	3	4	5	6	9	12	15
1,18	23,5	54	59	63	63	66	64	61	57	53
	16,5	28	38	39	36	36	37	35	33	31
0,113	32,1	69	78	61	55	48	45	36	31	31
	15	61	65	59	52	45	39	32	32	32
	9,8	36	36	30	31	31	31	33	30	31

The velocity $\bar{u}_y$ as a function of flow-rate concentration for small particles is presented in Fig. 3b. It is remarkable that the tendency for a decrease of $\bar{u}_y$ as μ increases obtained earlier theoretically [3] and identified for large particles [14] holds for small particles as well.

We also note that there are no appropriate correlations for $\bar{u}_y$ to date. In approximate calculations over the flow-rate concentration range $\mu = 1\text{-}15$ data of the present work permit us to recommend for small particles (d = 0.1-0.3 mm)

$$\bar{u}_y = 0{,}1 - 0{,}05\bar{u}_x \tag{8}$$

and for large ones (d = 0.8-3.5 mm)

$$\bar{u}_y = 0{,}2 - 0{,}1\bar{u}_x. \tag{9}$$

To determine the total velocity restoration factor, a device is developed whose schematic diagram is shown in Fig. 4a. The device is based on the idea of determination of velocity and angle of motion for a single particle before and after the collision with the considered surface. The principle of determining velocity is that of transit time. The upflight velocity vector is always directed downwards, and the angle of upflight is specified by the corresponding setting of contact plane 1.

Figure 4b gives the total velocity restoration factor n versus the upflight velocity at a fixed angle of attack equal to 32°. In the experiment use was made of spherical particles of diameter 1.00-1.04 mm and density 2600 kg/m^3. The specimen of the inner wall of a channel which was long used for pneumatic transport of the above particles served as a contact plane.

The run of the curve in Fig. 4b shows that the earlier existed notion of the factor n as of some fixed value for the given dispersed material is contrary to fact. As can be seen, the particle interaction with the wall is of a stochastic character due to the state of contacting surfaces.

Table 1 gives the results of calculation of ΔP_{dr} by formula (5) for glass spherical particles. The value of ΔP_0 was determined experimentally. The value of n for large particles is taken equal to 0.85 on the basis of the results presented in Fig. 4b. For fine particles n = 0.80 from the data of [9].

Attention is called to the fact that, with different velocities of the carrier gas flow, the contribution of ΔP_{dr} to the total drop ΔP_0 in the region $\mu > 6$ is identical for small particles, and there is a large spread in it for large particles. This is likely to be explained by the fact that the shielding effect for small particles shows up stronger than for large ones in the indicated region of μ. The problem is considered in more detail in [11, 15].

NOTATION

L, length of the channel portion, m; μ, flow-rate concentration of solid matter; S, channel cross-sectional area, m^2; D, diameter, m; ρ, gas density, kg/m^3; ρ_s, particle density, kg/m^3; m, mass of one particle, kg; d, particle diameter, m; $\bar{u}_x$, average longitudinal velocity, m/sec; $\bar{u}_y$, average transverse velocity, m/sec; $\bar{u}$, total average velocity of particle, m/sec; v, flotation velocity of particle, m/sec; ω, gas flow velocity, m/sec; $\Delta\bar{u}_x$, average value of variation in longitudinal velocity of particle at collision against the wall, m/sec; Δt_w, average free path time between two successive collisions against the wall, sec; f, density of particle collisions against the wall, $1/(m^2 \cdot sec)$; n, total velocity restoration factor; ΔP_0, total pressure loss of a gas flow, Pa; ΔP_{dr}, pressure loss of a gas flow due to particle collisions against the channel wall, Pa.

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