EXPERIMENTAL INVESTIGATION OF FLUCTUATIONS IN THE VELOCITY OF THE SOLID PHASE IN A FLUIDIZED BED

Yu. E. Livshits and A. I. Tamarin

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The results are given on a spectral-correlation analysis of fluctuations in the velocity of the solid phase in installations having diameters of 0.3 and 0.7 m in a free fluidized bed, and one retarded by low-volume checkers, of sand (d = 0.23 mm) and silica gel (d = 0.19 mm).

To construct reliable physical models of a fluidized system one needs information about the local characteristics of the motion of the solid phase, particularly on the frequency and amplitude of pulsations in the velocity of the particles in the fluidized bed.

Data on the motion of individual marker particles in a bed, which were obtained on model installations of small size (up to 0.23 m in diameter) using relatively large particles (1-4 mm), are presented in the literature [1-3]. Information is absent on pulsations in the velocity of the solid phase in a fluidized bed of fine particles or on the influence on them of the size of the installation, the height of the bed, and the fluidization mode, as well as of low-volume checkers, which find wide application for the improvement of the hydrodynamics of a fluidized bed [4].

The fields of average and pulsation velocities of the solid phase in a free fluidized bed and one retarded by low-volume checkers were measured and analyzed earlier in [5]. The present article continues these investigations. In it we give a spectra-correlation analysis of the fluctuations in the velocity of the solid phase.

The pulsations in the velocity of the solid phase were measured in columns 0.3 and 0.7 m in diameter. Sand (d = 0.23 mm, u_0 =0.06 m/sec) and silica gel (d = 0.19 mm, u_0 = 0.02 m/sec) were fluidized in the column with D_i = 0.3 m with an initial bed height H = 0.45 and h = 0.2 and 0.4 m. In the column 0.7 m in diameter we used only sand with H = 0.5 and 0.9 m and h = 0.52 and 0.92 m. The procedure for conducting the tests is given in more detail in [5].

An analysis of the average and pulsation velocities of the solid phase in a fluidized bed [5] showed that the movement of the material represents a steady random process. One of the main characteristics of such a process is the autocorrelation function [6-8]. The normalized autocorrelation function for each test was calculated by the algorithm of [6, 7] on a computer for an array of about 2000 points, selected with an interval of 0.0.2 sec and with a maximum shift τ = 4 sec.

Characteristic normalized autocorrelation functions for the fluctuations in the velocity of the solid phase in an installation 0.7 m in diameter are given in Fig. 1a. As seen from the figure, the autocorrelation functions fall off sharply from one to a level of less than 0.2 in a time of 0.1 sec. Their behavior is markedly different in the section from 0.1 to 1 sec. For τ >1 the value of R(τ) did not exceed 0.1 in all the tests. The autocorrelation function periodically changes sign. Physically this means [6, 7] that there is a periodic component of the pulsations in the velocity of the solid phase in the system, which is evidently connected with the passage of gas bubbles through the fluidized bed. Autocorrelation functions of fluctuations taken in the installation 0.3 m in diameter are similar.

Knowing the autocorrelation function, it is simple to determine the integral spatial scale [9, 10], which in the given case reflects the size of a "cloud" of particles moving with close velocities,

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A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk.
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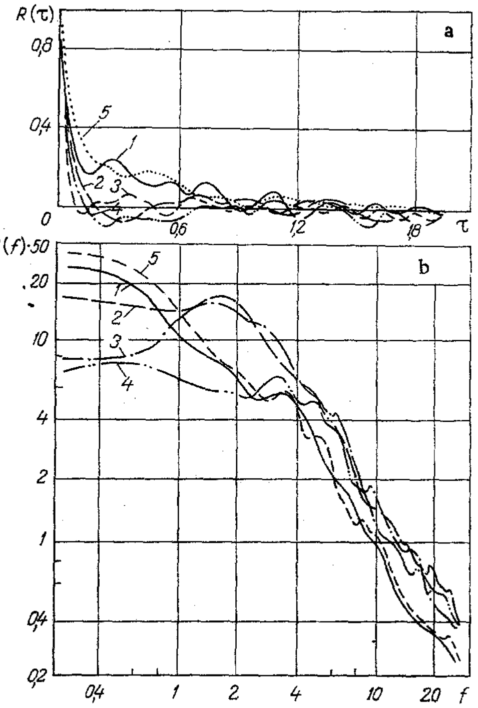

Fig. 1

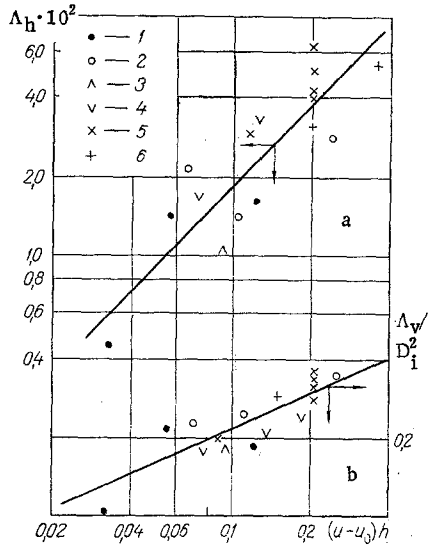

Fig. 2

Fig. 1. Autocorrelation functions (a) and spectral distribution densities of pulsations in velocity of solid phase (b) in an installation 0.7 m in diameter: 1, 2) free bed, $u-u_0$ = 0.39 m/sec, h = 0.52 m, vertical and horizontal components; 3, 4) retarded bed, $u-u_0$ = 0.4 m/sec, h = 0.92 m, vertical and horizontal components; 5) free bed, $u-u_0$ = 0.16 m/sec, h = 0.92 m, vertical component; τ, sec; f, Hz; G(f) · 50, sec.

Fig. 2. Dependence of integral spatial scale of pulsations in velocity of solid phase on parameters of system (a: horizontally; b: vertically); 1, 2) sand, D_i = 0.3 m, h = 0.2 and 0.4 m; 3, 4) silica gel, D_i = 0.3 m, h = 0.2 and 0.4 m; 5, 6) sand, D_i = 0.7 m, h = 0.52 and 0.92 m. $\Lambda_h \cdot 10^2$ m; $(u-u_0)h$, m²/sec; Λ_v/D_R^2, 1/m.

$$\Lambda = J\sigma, \tag{1}$$

where $J = \int_0^\infty R(\tau)\,d\tau$ is the temporal correlation scale.

In a fluidized bed the average velocity of ordered movement of particles is far less than the pulsation velocity [5], so that the root-mean-square velocity of the solid phase enters into Eq. (1) [11].

The integral spatial scales of the velocity of the solid phase in the horizontal and vertical directions are given in Fig. 2. It is seen from the figure that Λ_h increases linearly with an increase in $(u-u_0)h$. A change in the material (sand to silica gel) does not affect the size of the integral scale. The diameter of the installation has a strong influence on Λ_v, while the dependence on $(u-u_0)h$ is weaker. The test data are described, with a root-mean-square deviation of 38% for Λ_h and 17% for Λ_v, by the expressions

$$\Lambda_h = 0.182\,(u-u_0)\,h, \tag{2}$$

$$\Lambda_v = 0.61\,[(u-u_0)h]^{0.5} D_i^2. \tag{3}$$

Attention should be drawn to the fact that the integral spatial scales depend on the same parameters as does the size of bubbles in the bed [12]. As is known [12], increases in the height above the gas-distribution grating and in the velocity of the fluidizing agent lead to growth of the gas bubbles, and this causes an increase in Λ. Estimates show that Λ_h comprises from about 0.2 to 0.6 of the radius of a bubble.

Low-volume checkers submerged in a bed break up the gas bubbles and hence decrease the integral spatial scales of the pulsations. For example, in a bed containing checkers (hydraulic diameter 3 cm) Λ decreases

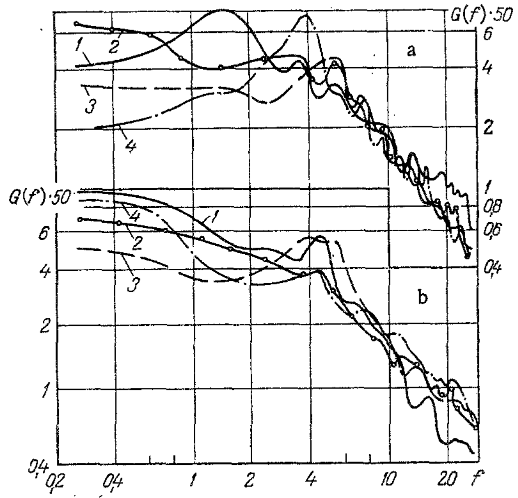

Fig. 3. Spectra of fluctuations in velocity of solid phase in an installation 0.3 m in diameter (a: vertical velocity component): 1, 2) sand, free bed, $u-u_0 = 0.26$ m/sec, $h = 0.4$ and 0.2 m; 3) sand, retarded bed, $u-u_0 = 0.6$ m/sec, $h = 0.4$ m; 4) silica gel, free bed, $u-u_0 = 0.34$ m/sec; $h = 0.4$ m (b: horizontal velocity component): 1, 2) sand, free bed, $u-u_0 = 0.6$ m/sec, $h = 0.4$ and 0.2 m; 3) sand, retarded bed, $u-u_0 = 0.6$ m/sec, $h = 0.4$ m; 4) silica gel, free bed, $u-u_0 = 0.45$ m/sec, $h = 0.4$ m.

by 4-10 times and does not depend on the height h or the gas velocity. It is the same in both the vertical and the horizontal directions and comprises 0.35 ±0.15 cm in the installation 0.3 m in diameter and 0.45 ±0.2 cm for $D_i = 0.7$ m. This indicates that the checkers make the system isotropic and homogeneous.

The spectral distribution density of pulsations in the velocity of the solid phase was determined through a Fourier transformation of the autocorrelation function using a Bartlett weight function [5-7].

Measurements in the column 0.7 m in diameter ($h = 0.52$ m) showed that the normalized spectra of the vertical and horizontal components of the velocity of the solid phase do not depend, within the limits of accuracy of the measurements, on the point of measurement over the radius of the installation. Characteristic normalized spectral distribution densities of the velocity of the solid phase in the installations 0.3 and 0.7 m in diameter are presented in Fig. 1b and Fig. 3 on a logarithmic scale. As seen from the figures, two characteristic regions can be distinguished in the spectra: a low-frequency region, where the pulsation energy is distributed relatively uniformly, and a damping region, where the amplitude of the velocity fluctuations declines continuously with an increase in frequency. The boundary of these regions lies approximately in the intervals of 4.5-5 Hz ($D_i = 0.3$ m; see Fig. 3) and 3.5-4 Hz ($D_i = 0.7$ m, see Fig. 1b). Changing the parameters of the system (size of installation, bed height, velocity, gas filtration) or the direction of the pulsations affects mainly the low-frequency region of the spectrum. The zone of damping of the oscillations changes little. Only low-volume checkers submerged in the fluidized bed lead to some increase in energy in this range, correspondingly lowering the pulsation level in the low-frequency region (see Fig. 1b, curves 3 and 4 and Fig. 3a, b, curves 3). A change in the material—a transition from sand to silica gel—does not introduce additional features into the spectra of fluctuations in the velocity of the solid phase (Fig. 3a, b, curves 4).

Peaks which, as already mentioned in the discussion of autocorrelation functions, indicate the presence of a periodic component in the original random signal, are well seen in the experimental spectra. The frequencies in the region of which a rise is noted lie in the range of 1.5-4 Hz for the installation 0.7 m in diameter and 3-5 Hz for $D_i = 0.3$ m. And lower frequencies correspond, as a rule, to a lower height above the gas-distribution grid.

The presence of periodicity in the random process of particle movement in a fluidized bed has also been noted by the authors of [1, 2]. This periodicity, as the authors of [1] assume, determines the most characteristic frequency of velocity change in the process of particle motion in the bed.

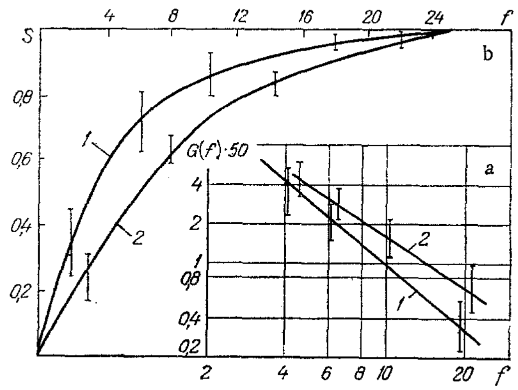

Fig. 4. Average spectral distribution density of fluctuations in velocity of solid phase in high-frequency region (a) and integral frequency distribution of pulsation energy (b): 1, 2) for installations 0.7 and 0.3 m in diameter; G(f) · 50, sec.

As already mentioned, starting with 3.0–3.5 Hz for a column 0.7 m in diameter and with 4.0–4.5 Hz for D_i = 0.3 m, the spectra hardly depend on the parameters of the system and are not even affected by low-volume checkers. For this frequency region we present in Fig. 4a, the values of the spectral density, averaged over all the tests, and their confidence limits with 90% probability for installations of both scales. The resulting dependences can be described by the simple function

$$G(f) = kf^{-n}, \tag{4}$$

where k = 0.8 and 0.54 while n = 1.63 and 1.3 for columns 0.7 and 0.3 m in diameter, respectively. Using the dependences obtained and the correlation determining the pulsation velocity [5], one can estimate the distribution of fluctuations in the velocity of the solid phase in the high-frequency region.

It is interesting to note that for the larger installation the exponent in (4) is close to the $-5/3$ obtained by Kolmogorov for the inertial interval of a turbulent-flow spectrum [9]. It is possible that in a fluidized system, too, the energy of the pulsation motion of the solid phase due to the passing through of gas in the form of bubbles is gradually transferred in stages from larger to smaller vortices and finally dissipates at scales comparable with the particle diameter. And this probably explains the stability of the spectrum in the high-frequency region. The departure from a $-5/3$ power for the installation 0.3 m in diameter is possibly connected with the influence of the walls in a column of smaller size.

For a clearer concept of the energy distribution of the fluctuation motion of the solid phase from the spectrum, in Fig. 4b, we present values of the integral $S = \int_{0.25}^{f} G(f)\,df$ and its confidence limits with 90% probability for installations 0.3 and 0.7 m in diameter. This dependence reflects the fraction of fluctuation energy of the solid phase falling into the corresponding region of the frequency range. The upper limits of the confidence intervals correspond to the conditions when the experiments were conducted in a free bed at a large height above the gas-distribution grid. The lower limit corresponds to the energy distribution in a bed containing checkers. As seen from the figure, for the installation 0.7 m in diameter most of the fluctuation energy (up to 70%) lies in the frequency band up to 7 Hz. In the installation 0.3 m in diameter this same fraction of the fluctuation energy is distributed in the frequency band up to 10 Hz, i.e., under the experimental conditions an increase in the scales of the system leads to a shift of the intensity of the fluctuations in the velocity of the solid phase into the lower-frequency region.

Thus, the investigations which were conducted showed that in a developed fluidized bed the pulsations in the velocity of the solid phase are distributed in two characteristic frequency regions. Most of the pulsation energy of the solid phase is concentrated in the low-frequency region, and the pulsation scale in it is determined by the sizes of the gas bubbles for a freely fluidized bed, while in a retarded one it is determined by the elements of the low-volume checkers. In the damping region the frequency distribution of the energy does not depend on a change in the parameters of the given system and can be described by the simple relation (4).

NOTATION

D_i, d, diameter of installation and average particle diameter; u, u_0, velocity of gas filtration in an empty cross section of the installation and velocity of start of fluidization; f, frequency; H, h, initial height of charge of material and height above gas-distribution grid; I, Λ, temporal and spatial integral scales of fluctuations in velocity of solid phase; ρ, density of material; σ, σ^2, root-mean-square deviation from average velocity of motion of solid phase (pulsation velocity) and its dispersion; τ, time of shift; $R(\tau)$, estimate of normalized autocorrelation function; G(f), smoothed normalized estimate of spectral density. Indices: v, vertical, h, horizontal.

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