SOLID-PHASE VELOCITY PATTERNS IN FREE AND CONSTRAINED FLUIDIZED BEDS

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A dynamometer system has been used to measure the average and instantaneous velocities of the solid phase in systems of diameters 0.3 and 0.7 m; it is found that these quantities are affected by low-volume packing.

It has been found that the solid material is transported upwards at the bottom of a rising bubble in a fluidized bed [1-4] and descends along the sides of the bubble [3, 4].

Bubbles cause regular circulation [5-9] and random movements of the solid in the bed [10-13].

A thermometer anemometer has been used [9] to examine the average motion of the particles in a system of diameter 0.24 m; the pattern in a diametrical plane was symmetrical about the axis and altered on rotating the plane around this axis. The average mass flows were stable, but there were changes on halting and re-starting the flow of fluidizing agent. The mass velocity of the particles was dependent on the distance to the gas-distribution grid and on the gas-flow speed. However, the results for the particle speeds were doubtful because they differed by more than two orders of magnitude from the bubble speeds and did not agree with those of [8].

A general description has been given [7] of the movements of the solid in a large apparatus (cross section 1.5 m^2 and bed depths from 0.39 to 1.47 m). The circulation was very much dependent on the bed parameters; for example, deep beds (0.86 or 1.47 m) and low gas speeds resulted in the main descending flux occurring at the center. This central descending flux degenerated as the gas speed increased.

Interesting results have been given [8] for the circulation in a column of diameter 0.8 m; the resistance force and free space in the flux incident on the transducer were recorded.

The mass-flow speed was found to increase with the excess velocity of the gas $u - u_0$ and with the distance above the gas-distribution grid, whereas it fell as the particle diameter increased. However, there is some doubt over the assumption that the force acting on the transducer was proportional to the square of the flow speed because measurements [14, 15] show that the relationship is linear over a wide speed range.

The available evidence is limited and does not provide adequate information on the mean-velocity distribution. Also, there is virtually no evidence on the velocity fluctuations from point to point.

We have examined the velocity patterns in the vertical and horizontal directions for systems of various sizes, particularly as regards the effects of low-volume packing.

Dynamometers were used whose design and calibration have previously been described in detail [16]. The transducer consisted of a sphere of diameter 5.5 mm connected to an elastic plate bearing strain gauges via a wire of length 29 mm and diameter 0.5 mm. The natural frequencies of the devices were 120-200 Hz, the exact value being dependent on the thickness of the plate, and it was possible to record collisions of the solid phase with the sphere at frequencies of the order of 60-100 Hz. The probe recorded the instantaneous flow speed around the sphere (the sensing element), or rather the projection of the speed on an axis perpendicular to the plane of the elastic plate.

Systems of diameter 0.3 and 0.7 m were used. The distribution grid in the column of diameter 0.3 m consisted of two layers of closely woven cloth clamped between two metal plates having holes of diameter 1.5 mm providing 20% free cross section. The design of the column with $D_C = 0.7$ m was similar. The diameter of the holes was 10 mm, while the free cross section was 11.5%, and a layer of wadding of thickness 9 mm was held between the perforated plates.

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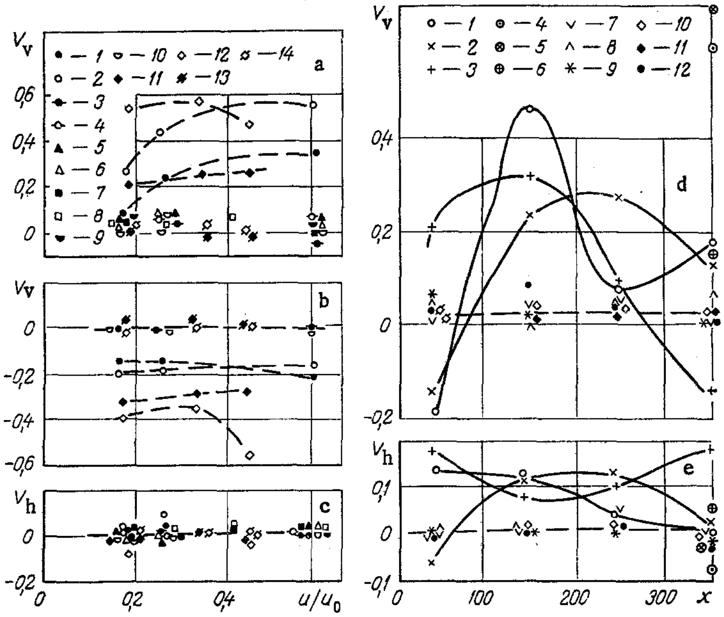

Fig. 1. Mean speed of solid in relation to gas speed and system size for free and constrained fluidized beds: a) vertical component of the velocity at the axis for D_c = 0.3 m; b) vertical component at the wall, D_c = 0.3 m; c) horizontal component at the axis, D_c = 0.3 m; 1, 2) free bed, sand, h of 0.2 and 0.4 m; 3, 4) spiral packing, sand, h of 0.2 and 0.4 m; 5, 7, 9) sand, horizontal grids of pitch 24, 17, and 36 mm, h = 0.2 m; 6, 8, 10) sand, horizontal grids of pitch 24, 17, and 36 mm, h = 0.4 m; 11, 12) free bed, silica gel, h of 0.2 and 0.4 m; 13, 14) spiral packing, silica gel, h of 0.2 and 0.4 m; d) vertical component in relation to radius for D_c = 0.7 m; e) horizontal component in relation to radius, D_c = 0.7 m; 1-3) free bed, h = 0.52 m, $u - u_0$ = 0.39, 0.24, and 0.16 m/sec; 4-6) free bed, h = 0.92 m, $u - u_0$ = 0.39, 0.24, and 0.16 m/sec; 7-9) grids of pitch 17 mm, h = 0.52 m, $u - u_0$ = 0.39, 0.24, and 0.16 m/sec; 10-12) grids of pitch 17 mm, h = 0.92 m, $u - u_0$ = 0.51, 0.4, and 0.16 m/sec; V in m/sec and x in mm.

The material was fluidized with air at room temperature; the air-flow speed was measured with calibrated diaphragms with an error not more than 3%.

The powder in the column of diameter 0.3 m was sand (d = 0.23 mm, ρ = 2600 kg/m^3, u_0 = 0.06 m/sec) or silica gel (d = 0.19 mm, ρ = 1100 kg/m^3, u_0 = 0.02 m/sec), but only sand was used in the system of diameter 0.7 m. The air speed for the sand was varied over the range 0.18-0.66 m/sec, while the corresponding range for silica gel was 0.14-0.47 m/sec.

The depth of the initial bed for D_c = 0.3 m was 0.45 ± 0.02 m, as against 0.5 or 0.9 m for D_c = 0.7 m. The transducer was set horizontally along the diameter of the column. Measurements were made at 0.2 and 0.4 m above the grid along the axis of the apparatus at 3-4 cm from the wall for D_c = 0.3 m, or at 0.52 and 0.92 m at four points along the radius (350, 246, 143, and 40 mm from the wall) for D_c = 0.7 m.

The retaining packing in the 0.3-m column was composed of spirals of diameter 50 mm wound from wire of diameter 2.5 mm with a pitch of 10 mm together with horizontal grids of cell size 7 × 7 mm with pitches of 35, 24, or 17 mm, whereas only horizontal grids of pitch 17 mm were used for D_c = 0.7 m.

The transducer signal was proportional to the speed of the solid phase and was recorded with N-327-1 chart recorder. At the same time, the signal was digitized and processed by computer. The appropriate length for a single realization was defined from the condition that the mean value should be stationary [17]. A realization of length 30-40 sec was sufficient because the mean value remained constant within 5% on increasing the length further.

The sampling interval was defined from a preliminary analysis of the fluctuations at the maximum flow speed.

The mean value of the square of the signal at frequencies above 25 Hz was only 3-5% of the total; there were no fluctuations of frequency above 60 Hz, and therefore a sampling interval of 0.02 sec is sufficient [12].

Figure 1 shows the projection of the mean speed of the solid on the vertical and horizontal axes for the systems of diameters 0.3 and 0.7 m for a free bed and a constrained one.

Figure 1a shows that the coherent motion of the material along the axis is upwards in a free bed in the apparatus of diameter 0.3 m; the mean speed of the material varied with the flow rate for a given initial bed depth and also increased considerably away from the distributing grid (h of 0.2 and 0.4 m). The material at the wall moves downwards (Fig. 1b).

The vertical component of the mean speed in the free bed is shown in relation to the radius in Fig. 1d for three values of the excess gas speed (0.16, 0.24, and 0.39 m/sec). There is considerable nonuniformity in the velocity profile. In the smaller column (0.3 m), the material at the center always rises, whereas that at the wall descends, while the exact pattern in the larger system (0.7 m) is dependent on the flow speed. Moreover, excess speeds of 0.39 and 0.24 m/sec result in the material descending at the wall, whereas the material there rises at the lower speed of 0.16 m/sec. As in the case of the 0.3-m column, the mean speed of the material increased substantially with the distance from the distribution grid.

The motion of the bubbles (see [19] for method of measurement) and the speed of the solid were examined together; the highest mean speeds of the material occurred in places where bubbles are frequent and move at high speeds.

The average pattern for the convective circulation is in agreement with other results [6, 8]; it has been shown [6] that this form of circulation is related to the nonuniform distribution of the bubble fluxes in such a system even when a porous distribution grid is used. The points of most rapid bubble formation in a large apparatus lie on a ring, where the flux of material is also largest.

Figure 1c and e show the projections of the mean speeds on the horizontal (perpendicular to the axis of the transducer). The positive direction was taken as being to the right from the axis of the transducer. The material rose along the axis and descended at the wall in the smaller column; the mean horizontal speed was zero (Fig. 1c).

The projections on the vertical and horizontal axes (Fig. 1d and e) imply that the steady-state pattern for the circulation in a column of diameter 0.7 m is dependent on the gas speed.

The steady-state circulation controls the general transport in a fluidized bed; also, random particle movements occur, which can be described in terms of turbulent transport. The rms speed of the solid characterizes this feature.

Figures 2 and 3 show results for the random components in the vertical and horizontal directions for columns of diameters 0.3 and 0.7 m for various speeds and various positions of the transducer.

Figures 2a and 3a show that the random vertical speed in a free bed increases with the gas speed and with the distance above the grid, while the rate of increase is dependent on the characteristics of the material (Fig. 2a). The values for silica gel were lower than those for sand.

Figures 2c and 3c similarly give the horizontal components for the same conditions. Here the horizontal projection also increases with the gas speed and with the distance from the grid.

Figures 2a, 3a, and 3c show that the random component of the speed is very much less dependent on the position in the apparatus than is the mean speed.

The ratio between the vertical and horizontal components of the random speed lies in the range 1.1-3.5; the lower values relate to the lower gas speeds, so the random movement is not isotropic in an unevenly fluidized bed because the vertical component is higher than the horizontal one.

The random component reflects the kinetic energy of the disorderly motion; the horizontal components of the random velocity are symmetrical about the vertical axis, and therefore the energy of the random motion is proportional to $\sigma_v^2 + 2\sigma_h^2$; the energy of the convective flux corresponds to the time-average of the velocity and is proportional to $V_v^2 + V_h^2$ because $V_v > V_h$. The ratio of the random energy to the coherent energy averaged over the cross section is $\sigma_v^2 + 2\sigma_h^2 / V_v^2 + V_h^2$, and this increases with the gas speed and varies within limits of 11-25.

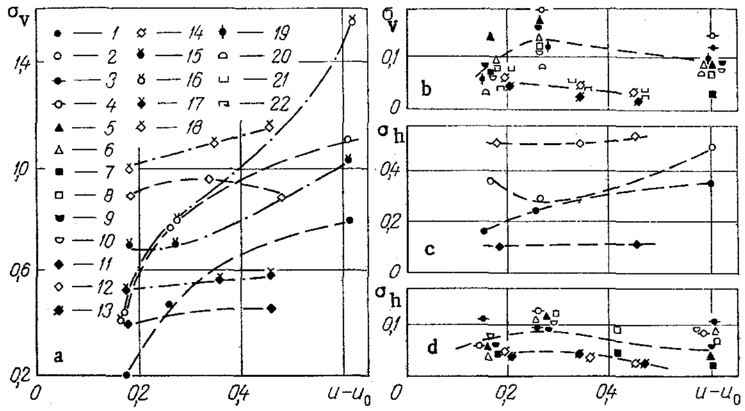

Fig. 2. Random component of velocity in relation to gas speed for a column of diameter 0.3 m; a, b) vertical component at the axis and at the wall for a free bed (a) and a constrained bed (b); c, d) horizontal component of the random velocity at the axis in a free bed (c) and a constrained bed (d); at the axial: 1, 2) free bed, sand, h = 0.2 and 0.4 m; 3, 4) spiral packing, sand, h of 0.2 and 0.4 m; 5, 7, 9) horizontal grids of pitch 24, 17, and 36 mm, sand, h = 0.2 m; 6, 8, 10) horizontal grids of pitch 24, 17, and 36 mm, sand, h = 0.4 m; 11, 12) free bed, silica gel, h of 0.2 and 0.4 m; 13, 14) spiral packing, silica gel, h of 0.2 and 0.4 m; at wall: 15, 16) free bed, sand, h of 0.2 and 0.4 m; 17, 18) free bed, silica gel, h of 0.2 and 0.4 m; 19, 21) spiral packing, h of 0.2 m, sand and silica gel; 20) grid of pitch 36 mm, sand, h = 0.4 m; 22) spiral packing, silica gel, h = 0.4 m; σ and $u - u_0$ in m/sec.

Indirect evidence for these conclusions comes from measurements on the forces acting on a body immersed in the bed [20], which are proportional to the speed of the solid [21]. Therefore, the energy in the random motion exceeds that in the coherent motion by an order of magnitude or more.

We therefore examine in more detail the relationship between the random energy and the system parameters (excess gas speed, height above grid, and diameter).

Figure 4 shows $E = \sqrt{\sigma_v^2 + 2\sigma_h^2}$ in relation to these parameters for the 0.3 and 0.7 m systems. The following equation fits the measurements over the ranges used:

$$E = 5\,[(u - u_0)\,hD_h]^{0.5}, \tag{1}$$

where all the parameters are in SI units.

The argument in (1) is $(u-u_0)h$, which governs [19] the size of the gas bubbles and the mean bubble rise speed. This quantity reflects the power consumed in passing the gas through the bed, and some of this energy is taken up by the random movement. Also, the energy of (1) is dependent on the size of the column, as a larger fraction of the input energy is consumed by the random movement as the size of the apparatus increases. Further, (1) defines the rms speed of the solid in a fluidized bed within the range covered by the measurements.

A low-volume packing in the bed alters the pattern substantially; Fig. 1a, b, and d show that the mean vertical speed is independent of the gas speed, the distance from the grid, and the size of the apparatus. The mean rate of rise of material in a retained bed is lower by an order of magnitude than that in a free bed and varies over the range 3-6 cm/sec. Therefore, the packing very much impedes the steady-state circulation.

The exact details of the packing do not affect the mean speed (Fig. 1a and b). The packings used were similar in hydraulic diameter (from 1.85 to 3 cm), and the effects on the system were identical. This applies fully to both of the materials, although these differ by a factor of 3 in critical fluidization speed.

Figures 1c and d show the horizontal components for the systems of diameter 0.3 and 0.7 m; the mean speed is close to zero no matter what the type of packing, gas speed, or point of measurement. Therefore, the packing suppresses consistent horizontal movement of the material.

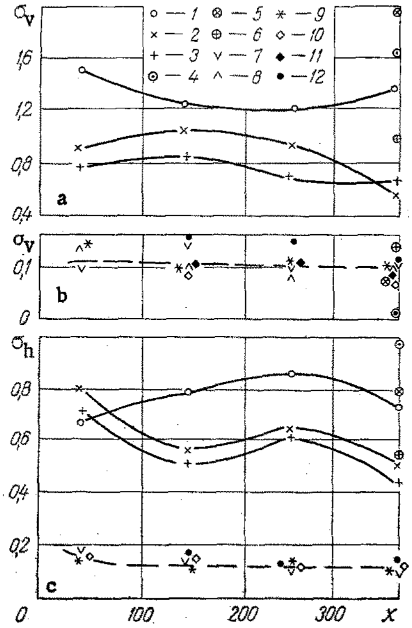

Fig. 3. Random velocity of the solid in a column of diameter 0.7 m: a, b) vertical projection of the random velocity in a free bed (a) and a constrained bed (b); c) horizontal projection of the random velocity in free and constrained beds: 1-3) free bed, h = 0.52 m, $u - u_0$ = 0.39; 0.24; 0.16 m/sec; 4-6) free bed, h = 0.92 m, $u - u_0$ = 0.39; 0.24; 0.16 m/sec; 7-9) horizontal grids of pitch 17 mm, h = 0.52 m, $u - u_0$ = 0.39; 0.24; 0.16 m/sec; 10-12) horizontal grids of pitch 17 mm, h = 0.92 m, $u - u_0$ = 0.39; 0.24; 0.16 m/sec). σ, m/sec; x, mm.

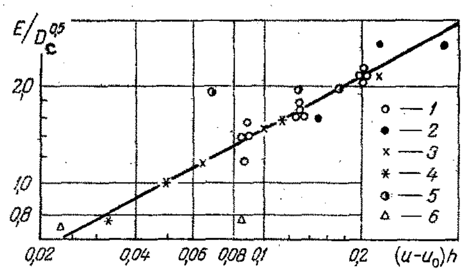

Fig. 4. Random component of velocity in relation to system parameters: 1, 2) sand, D_c = 0.7 m, h = 0.52 and 0.92 m; 3, 4) sand, D_c = 0.3 m, h = 0.4 and 0.2 m; 5, 6) silica gel, D_c = 0.3 m, h = 0.4 and 0.2 m. $E/D_c^{0.5}$, $m^{0.5}$/sec; $(u - u_0)h$, m^2/sec.

Figures 2b and 3b give the random vertical speed component in a packed bed; the packing very much reduces the random energy (the rms velocity is reduced). The vertical component varies little with the depth of the bed and with the distance from the distributing grid, and it is also independent of the size of the apparatus. For example, the rms speeds for the systems of diameter 0.3 and 0.7 m containing sand were in the range 10 ± 6 m/sec. Somewhat lower rms speeds were found at the wall and in the bed for silica gel.

There is little difference between the horizontal and vertical projections of the random velocity in a constrained bed, and the random movement is largely isotropic.

The sand and silica gel results show that the two are influenced in different ways by the packing; the vertical and horizontal components of the random velocity for silica gel were lower than those for sand (Figs. 2b and d).

These results show that a fluidized system is anisotropic and inhomogeneous; the horizontal and vertical velocity projections differ and also vary with the position in the bed. An efficient low-volume packing renders the system homogeneous and isotropic, i.e., the random velocities are independent of direction and point of measurement.

NOTATION

u, u_0	are the gas flow speed in the free section and the critical fluidization velocity;
V_v, V_h	are the mean vertical and horizontal velocities;
D_c	is the column diameter;
d	is the mean particle diameter;
ρ	is the density;
h	is the distance from grid;
$E = \sqrt{\sigma_v^2 + 2\sigma_h^2}$	is the overall random velocity;
x	is the radial distance from wall;
σ_v, σ_h	are the vertical and horizontal random velocities.

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