in filtration of fluidizing agent through bed; ε, porosity of bed; ρ_s, ρ_f, density of particles and gas; τ, time.

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EFFECT OF BOUNDING SURFACES ON POROSITY DISTRIBUTION IN A GRANULAR MEDIUM

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An experimental study is made of porosity distribution in a granular bed close to one of the surfaces bounding it. It is shown that wall deformation reduces the nonuniformity of porosity and the velocity profile of the gas flow.

The flow of a liquid or gas in reactors with a stationary granular bed of catalyst is significantly affected by the properties of the bed [1], particularly the distribution of local porosity over the cross section of the apparatus.

Experimental results have been obtained on porosity distribution inside stationary beds of uniform spherical and cylindrical particles [2-5], but such results are very limited in volume and do not permit a full evaluation of the effect on porosity distribution of such properties of the bounding surfaces as deformability, roughness, etc. The present work thus attempts a more detailed study of the porosity distribution of a granular material near a flat boundary and the effect of the properties of the wall on this distribution.

Experimental Unit and Method

The experimental unit consisted of a rectangular vessel 400 × 200 × 200 mm made of organic glass. The vessel had a double bottom, with holes joining the filling chamber with the working volume containing the granular material. The fluid was delivered from a buret through the chamber and into the bed, filling the cavities in the latter. The height of ascent of the fluid in the granular bed h was fixed with a reading microscope and we established a physically small volume ΔV_2 for averaging the porosity of the thin bed. Bed porosity was determined as

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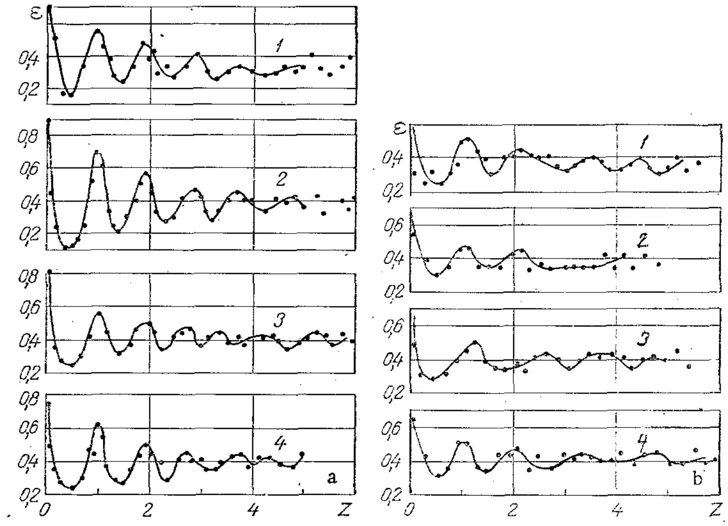

Fig. 1. Porosity distribution in a bed of spherical (a) and cylindrical (b) particles of different diameter: a – 1) D = 5.6; 2) 10; 3) 25; 4) 37; b – 1) D = 5; 2) 10; 3) 15; 4) 25 mm (Z = r/D, c – distance from wall).

$$\varepsilon = \frac{\Delta V_1}{\Delta V_2},$$

where ΔV_1 is the volume of fluid leaving the buret, equal to the volume of the cavities in the granular bed; ε is the distribution of porosity normal to the vessel bottom, which we will henceforth refer to as a wall.

Hard (Nondeformable) Wall

The above method was used to study the effect of a hard wall on the porosity distribution of monodisperse granular beds formed by the free fall of spherical and cylindrical particles into the working volume. We used steel balls 5.6, 10.2, 15.3, and 19.8 mm in diameter. We also studied beds of plastic and ceramic balls 37 and 25 mm in diameter, respectively. Figure 1a shows the porosity distribution, averaged for five different beds, as a function of distance from the wall.

It is apparent from the figure that the general character of the curves resembles curves of decaying vibrations with a constantly diminishing amplitude and a slowly changing period. The somewhat lower amplitudes (extreme values of porosity) for the ceramic balls is possibly due to the deviations from spherical form in these particles.

The reduction in period and gradual decrease in amplitude point to a change in bed structure going away from the wall, the structure of the bed initially (at the wall) being determined by the wall itself. The results in Fig. 1a are adequately described by the empirical relation

$$\varepsilon = \varepsilon_0 \exp(-\beta Z) \cos(BZ) + C,$$

where $\varepsilon_0 = 0.3$; $B = 2.2$; $\beta = 0.37$; $C = 0.4$ are mean values of quantities determined experimentally for spherical particles of the above-indicated dimensions.

Cylindrical pellets with a diameter equal to their height are presently used in industry in various production processes. Therefore, we studied the porosity distribution of granular beds composed of cylindrical particles with diameters of 5 mm (KNF catalyst), 10 mm (steel cylinders), and 15 and 25 mm (ceramic heat carriers). The measurements are shown in Fig. 1b in the form of graphs of porosity distribution normal to the wall. Comparison of the results with the corresponding distribution for beds of spherical particles reveals a certain reduction in extreme values of porosity in the bed of cylindrical particles.

Mean values of porosity for the entire bed of cylindrical particles agree with the corresponding values for beds of spherical particles and lie within the range 0.37–0.42, which differs somewhat from the data in [3].

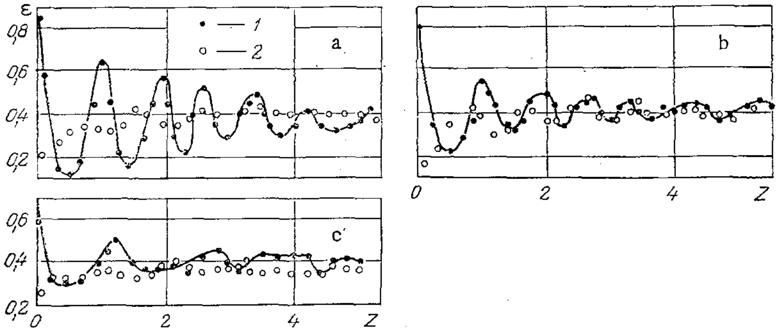

Fig. 2. Porosity distribution in a bed of spherical and cylindrical particles bounded by a deformable wall. The particle diameters: a) sphere, D = 15 mm, thickness of soft wall d = 5 mm; b) same, 25 and 15 mm; c) cylinders, 15 and 5 mm; 1 and 2) results of experiment for hard and deformable (soft) walls with the same particle sizes.

"Soft" (Deformable) Wall

The character of the change in porosity for a bed of granular material bounded by hard (nondeformable) walls shows that the structure of the bed is apparently nonuniform. It can be suggested that the degree of this nonuniformity depends on the properties of the surfaces bounding the bed and that a change in these properties will significantly affect the formation of the bed structure.

To check this hypothesis, we studied the porosity distribution in a granular bed bounded in the first case by a deformable surface (soft wall) and in the second case by a shaped surface in the form of a metallic grid. The deformable wall was a piece of porolon foam placed on the bottom of the working chamber, with the granular material then having been poured into the chamber. Measurements were made for beds consisting of spherical particles 10.2, 15.3, and 25 mm in diameter and cylindrical particles 15 mm in diameter. The data obtained were compared with the results for the hard wall (Fig. 2). It is apparent from the comparison that the amplitudes of the porosity fluctuations decrease and the fluctuations themselves decay at a shorter distance from the wall. The sharp decrease in porosity at distances less than 0.5 of a particle diameter can be explained by the filling of the cavities between the particles directly in contact with the wall by the material of the deformable (soft) wall. Here, the mean porosity for the entire bed of spherical particles remains roughly the same as in the case of a hard wall. The mean porosity in the bed of cylindrical particles turned out to be 0.02 lower with the soft wall than with the hard wall.

As shown by the experiments, the effectiveness of the effect of the deformable wall on porosity distribution depends on the thickness of the wall. Fluctuations in porosity occur with a lower amplitude and more rapid return to a constant value if the thickness of the soft wall is less than 0.5 particle diameter. Here, the particles directly in contact with the soft wall are "submerged" in the wall over one-third of their diameter. A further increase in wall softness does not lead to an appreciable change in porosity distribution. The amount of deformation of the wall (i.e., the depth to which the particles penetrate the wall) depends on both the elastic properties of the material and on the load placed on the wall by the bed. In our experiments, this load remained roughly the same with a change in the thickness of the soft wall.

Grid as the Bounding Surface

A metal grid was laid on the chamber bottom and the chamber was filled with spherical particles. We used grids with circular 12-mm openings and square 5-mm openings and steel balls 15.3, 10.2, and 5.6 mm in diameter. The measurements were close to those obtained with the soft wall. In all of the tests, the amplitude of the fluctuations was significantly reduced. The fluctuations decayed more rapidly, and the amplitude became roughly constant at a distance from the wall equal to three particle diameters. Here, the mean porosity of the entire bed was the same as in the case of the hard wall. The effect of a grid as the bounding surface proves to be more appreciable if the particle sizes are 20-30% greater than the size of the openings in the grid.

Since, as was shown above, the use of a deformable wall leads to a reduction in the amplitude of fluctuations in the porosity of a granular bed and thus makes the structure of the bed more uniform, it might be suggested that the use of a soft wall in a cylinderical apparatus with a stationary granular bed would alleviate the nonuniformity of the velocity profile of the gas flow passing through the bed.

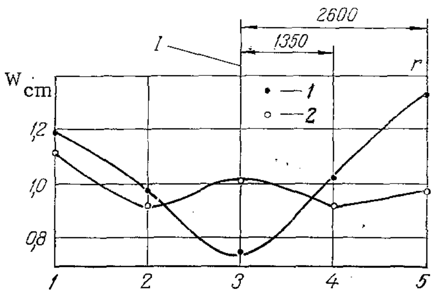

Fig. 3. Distribution of relative velocity of gas flow in a commercial reactor W_{cm}: 1) with normal loading of the reactor; 2) results of experiment with the loading of a reactor with a wall covered with a deformable material; I) center of reactor.

To check this hypothesis, we conducted a special experiment to measure the velocity profile of a gas flow in a 5.5-m-diameter commercial reactor. The monodisperse bed of granular KNF catalyst had a height $H = 2$ m. To impart elastic properties to the concrete wall of the reactor, it was covered with a layer of kaolin wool 30-40 mm thick. The reactor was operated in the regeneration regime. The method used to obtain the velocity measurements is explained in [6]. The measurements are shown in Fig. 3, which illustrates the distribution of relative velocity of the gas flow in the reactor $W_{cm} = W_r/W_{mn}$ (W_{cm} is the relative velocity of the gas flow); W_r, velocity of the flow measured over a given radius; W_{mn}, consumption-mean velocity of the gas flow over the cross section of the apparatus; r, running radius). It is apparent from the figure that the use of a deformable wall leads to a substantial reduction in nonuniformity of the gas-flow velocity profile.

Thus, by the representation of defined properties limiting the granular medium of the surfaces, one can actively regulate it by the distribution of the gas stream propagating through it.

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