INVESTIGATION OF THE STRUCTURE OF A FIXED GRANULAR BED USING COMPUTER AIDED TOMOGRAPHY

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We present the results of tomographic studies of the structural parameters of fixed granular beds which have been arranged using different methods.

The productivity of technological processes in which gas-phase matter is passed through a fixed bed of granular catalyzer depends, to a great extent, on particle distribution throughout the bed volume. A series of works [1-5] showed the influence of the method of packing the granular bed on the appearance of aerodynamic nonuniformities in the gas flow. These nonuniformities lead to a reduction of the working efficiency of the chemical apparatus. In [4], different methods were proposed for arranging the granular bed in order to create a uniform packing.

A method of pouring finely dispersed, granulated material was proposed in [6] for control of the granular bed structure. This method allows study of the large-scale nonuniformities which arise during bed loading, but only permits measurement of characteristics integrated over height.

In this work, we used one of the introscope methods to investigate the internal structure of granular beds: the method of computer-aided tomography (CAT). CAT virtually ideally solves diagnostic problems of nondestructive control. Without destroying the integrity of the subject, the method reproduces an image of spatial cross sections with elements of the structure, to a high degree of accuracy.

The essence of the method lies in the reconstruction of local characteristics of the spatial distribution of the line coefficients of attenuation (LCA) of x-ray radiation in the volume of the subject. This is done in terms of a set of integral shadow projections obtained during irradiation of the subject from different directions.

LCA values for each elementary volume cell of a cross section of the subject body are determined with the help of a computer used specialized algorithms. We used the medical SOMATOM DR-2 CAT to study our samples. This device transforms the measured LCA values into contrast (CT) values with the use of the international Hounsfield (Hu) scale:

$$\mathrm{CT} = \frac{\mu - \mu_{water}}{\mu_{water}} \cdot 10^3, \tag{1}$$

where μ is the line coefficient of attenuation which characterizes the relative decrease in radiation intensity after the radiation transits a 1-cm thickness of the absorbing medium.

This scale is defined so that water is assigned a value Hu = 0; and air, −1000 Hu. A material with a high density corresponds to 3000 Hu or more. The range of Hu values from −1024 to 3071 is expressed by the appropriate brightness level on the half-tone screen display. The most important characteristic of CAT is the capability to resolve according to contrast: the ability of CAT to detect small differences in material density of the subject. In other words, CAT detects differences in the CT numbers for these regions:

$$\Delta(\mathrm{CT}) = (\mathrm{CT}_2) - (\mathrm{CT}_1) = \frac{\mu_2 - \mu_1}{\mu_{water}}. \tag{2}$$

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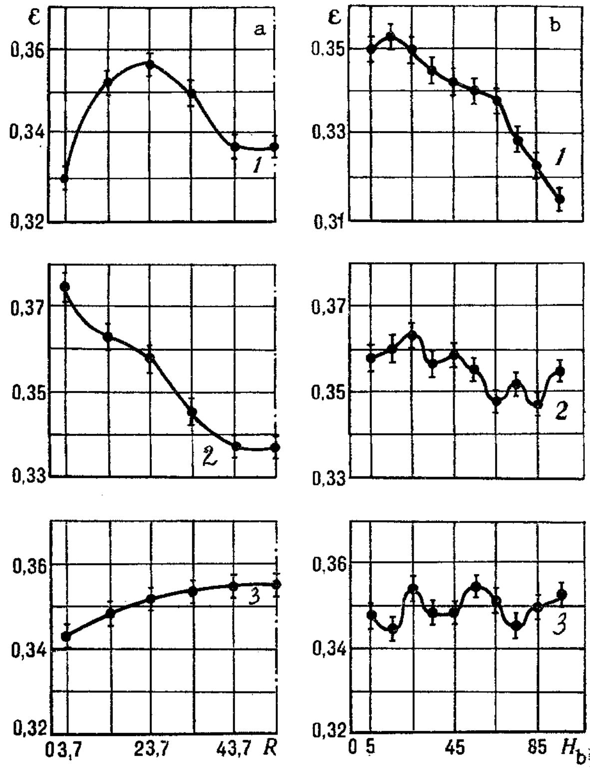

Fig. 1. Distribution of porosity by container section (a, by radius; b, by height) for different types of loading: 1) cone; 2) conical funnel; 3) spiral from the wall. R and H_b are in mm.

The resolution of the SOMATOM DR-2 CAT in terms of contrast is 0.1%.

The basis for application of the CAT method for control of some types of industrial manufacturing was introduced in [7]. That work gave the analytical equations for quantitative analysis of the basic technical and metrological characteristics of the method.

With the help of high spatial resolution, [8] determined the parameters of the internal structure of composite materials. Statistical analysis of these results made it possible to construct a volume function of density distribution and to pick out three factors influencing this distribution in the composite. These are: the presence of reinforcing filler, polymer, and microvoids in the material, and the predominance of one of these in different regions of the composite.

Experimental Method. The goal of this work is to study the nonuniformities in the structure of a granular bed which arise as a result of different methods of arranging the bed. One of the most important characteristics of a granular medium is its porosity: $\varepsilon = V_v/V_b$.

Since $\mu = \rho \cdot \mu_m$, we can establish, by a straightfoward transformation, a connection between the porosity and LCA (CT value):

$$\varepsilon = 1 - \frac{1 + \mu_i \cdot 10^{-3}}{1 + \mu_0 \cdot 10^{-3}}, \tag{3}$$

where μ_i is the elementary cell LCA measured in Hu; and μ_0 is the LCA of a monolithic sample, in Hu.

In keeping with the goal of the study, we selected a high-contrast resolution regime, which allowed us to visualize and estimate the density change in the subject. The image of the subject cross section (tomogram) is a matrix of LCA values consisting of 256 × 256 pixels (elements). A matrix element is characterized by the so-called ZOOM-factor, defined as the dimension of the image element. In our case, for increased resolution, we chose the maximum ZOOM-factor, equal to 10. This value corresponds to the minimum dimension of the image element of 0.216 mm.

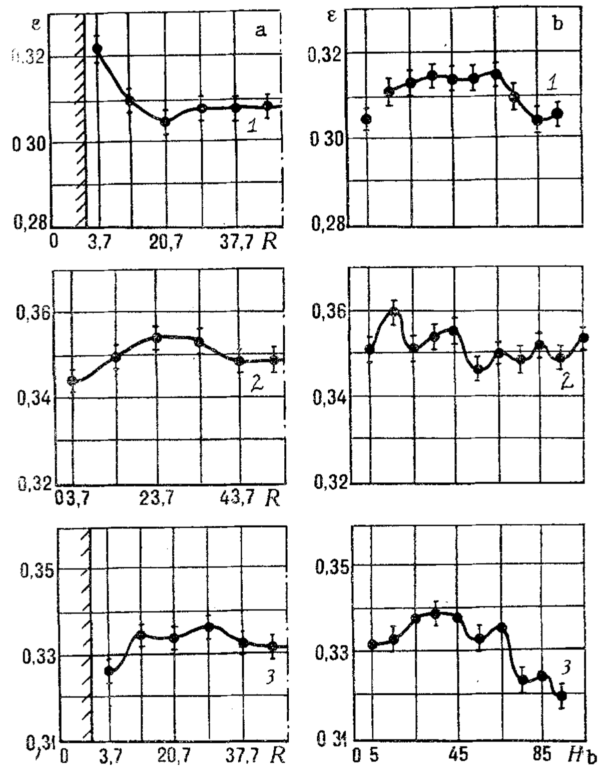

Fig. 2. Distribution of porosity by container section (a: by radius; b: by height) for different types of loading: 1) "Soft wall" + cone; 2) spiral from center; 3) "Soft wall" + spiral from center.

Modelling of the different structures of a granular material was done in a cylindrical container made of organic glass with a diameter and height of 100 mm. Alumosilicate particles of dimension 0.3 mm were used as the granular material. For each alumosilicate fill, six tomographic slices were made at 60° intervals. These results were combined and averaged by instrumental and computational means, and then put on the display screen and recorded on paper tape.

Thus, for each alumosilicate fill, a matrix of LCA distribution was obtained, which, using (3), was reconstructed into a matrix of porosity ε distribution. The quantity μ_0 was determined from a specially pressed sample. Then the matrix of 256 × 256 LCA elements was averaged over a 10 × 10 dimension.

For comparison of the distribution of nonuniformities by container cross section, we computed averaged expressions for the porosity as a function of radius (Figs. 1a, 2a) and of height (Figs. 1b, 2b) of the container. The graphs, like the tomograms, clearly show the distribution of local and large-scale nonuniformities.

Different methods of loading the container were used to study the effect of loading on the emergence and distribution of structural nonuniformities of the granular bed. These were: on a cone, through a conical funnel, and in a spiral.

Tomograms of perpendicular cross sections, averaged over three packings of the same type, are shown in Fig. 3. The densely loaded regions are significantly darker, especially in the middle of the container (Fig. 3a, b). The layered nature of the structures which characterizes all types of loading is clearly visible.

Loading on a cone, whose dimension was 10% less than the container diameter was done in a pointed cone located inside the container and which was subsequently shifted upwards as the container filled. The averaged results are shown in the tomogram (Fig. 3a). The major large-scale nonuniformities at the bottom, near the wall and at the center of the container are very pronounced. These reach the upper boundary of the granular bed. The formation of these nonuniformities is related to the repacking of particles as they rebound from the container walls.

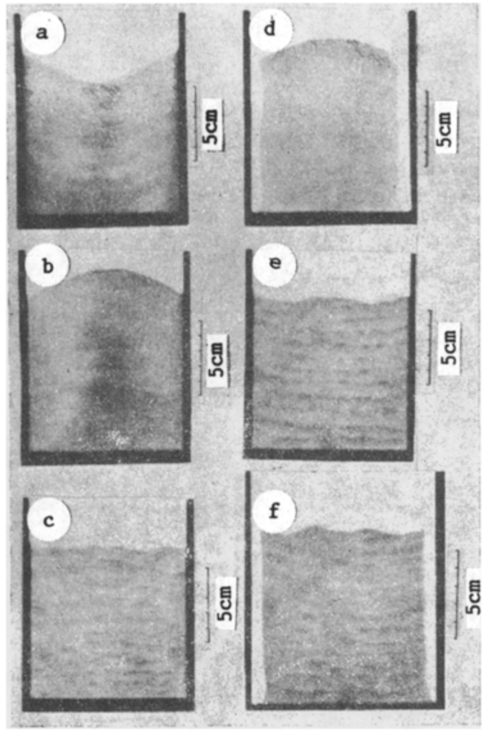

Fig. 3. Tomograms of various types of loading: a) cone; b) conical funnel; c) spiral from the wall; d) "soft wall" + cone; 3) spiral from center; f) "soft wall" + spiral from center.

The porosity distribution as a function of container radius is shown in Fig. 1a. Initially, the porosity grows from the container wall to the half-radius, then gradually declines towards the center. The plot quantitatively illustrates the presence of large-scale nonuniformities along transverse zones in the container. The porosity distribution as a function of container height (Fig. 1b, curve 1) shows that it decreases towards the bottom of the container, from 0.355 to 0.318.

Loading through the conical funnel took place at the center of the container. From the tomogram (Fig. 3b), it is clear that most of the large-scale nonuniformity is at the center of the container.

The averaged porosity distribution as a function of container radius for this type of packing is shown in Fig. 1a, curve 2. This curve shows a gradual undulating decrease from the container wall to its center. The porosity distribution with container height, shown in Figs. 1b, and 2b, shows an undulating decrease in porosity from the upper boundary to the bottom of 0.362 to 0.348.

Spiral loading (from the edge) took place from a short height from the container walls to the center with subsequent rotation and repetition of the cycle until the container was fully loaded. This loading (Fig. 3c) creates the most uniform packing throughout all container sections. The porosity distribution curve increases slightly from 0.342 to 0.354 towards the container center (Fig. 1a, curve 3). The distribution of porosity with container height (Fig. 1b, curve 3) is practically uniform (ε = 0.350) within the limits of the confidence interval when averaged over three loadings.

Figures 2a, and 2b (curve 2) show the results of spiral loading from the center of the container. This loading differs somewhat from the previous case, since the porosity distribution has a bulge at 0.5 radius, but it also can be considered as reasonably uniform.

In [4], one of the methods of eliminating nonuniformities in catalyst loading in a chemical reactdor is the proposed "soft wall." The wall of the axial adiabatic reactor was covered with a layer of kaolin wool, and the catalyzer was loaded in the usual way. Aerodynamic experiments on model walls and on industrial equipment showed a reduction in the nonuniformity of the gas flow velocity profile, measured under the container bottom.

To date, the question of the connection between the gas flow distribution under the container bottom and the structure of the granular medium inside the container has been controversial. The influence of the "soft wall" on the change in the internal structure of the granular bed has been verified by CAT. With this goal in mind, loading on a cone, which maximized large-scale nonuniformities, was chosen from among the special loading methods. A porolon foam 16-mm thick was used as a "soft wall" (Fig. 3d).

The results, shown in Fig. 2a, curve 1, indicate a decrease in large-scale nonuniformity. The porosity initially decreases from 0.323 to 0.305 up to the half-radius, and then grows insignificantly to 0.309. The distribution of porosity with container height (Fig. 2b, curve 1) shows an insignificant decrease at the base of the container and at the free surface of the bed. The same results for experiments with spiral loading (from the center) and with a "soft wall" do not in prinicple differ from the previous results (Fig. 2a, b, curve 3; Fig. 3e, f).

Thus, to a high degree of accuracy, CAT confirms the presence of local and large-scale nonuniformities in granular beds and their origin in the various methods of arranging the beds.

To solve practical problems, for example, for aerodynamic calculations of axial reactors or of loading devices, it is necessary to represent results in the form of analytical expressions for any point in a section of the device. To do this, the results for all of the packings presented here were interpolated using cubic splines in two variables [9]. The splines were constructed in the form of an expansion in terms of the tensor product of B-splines:

$$g(x, y) = \Sigma C_{i,j} B_i(x) B_j(y),$$
$$0 \leqslant i \leqslant 4, \quad 0 \leqslant j \leqslant 9,$$

where

$$B_i(x) = (x - i + 3)_+^3 - 4(x - i + 2)_+^3 + 6(x - i + 1)_+^3 - 6(x - i)_+^3 + (x - i - 1)_+^3,$$

and the same for $B_j(y)$.

From the given conditions, we formulated an 84 × 84 matrix defining a system of equations for the unknown coefficients $C_{i,j}$, where $0 \le i \le 4$; $0 \le j \le 9$.

In problems of this type, the matrix is diagonal in form, that is, it consists for the most part of zero elements. To solve the system, we applied a specialized method for use on sparse matrices. The calculations were done on an SM-4 computer. The results were printed out in the form of a rectangular system of numbers.

Thus, mathematical analysis using third-order B-splines allows us to describe the spatial cross sections of a packing in a granular material which has been arranged using different methods.

NOTATION

CT, magnitude of the contrast in Hu; μ, linear coefficient of attenuation in cm^{-1}; ε, porosity; V_v, void volume; V_b, bed volume; μ_m, bulk coefficient of attentuation in g^{-1}.

LITERATURE CITED

1. E. K. Popov, G. N. Abaev, et al., Promyshlennost' SK, No. 8, 1-5 (1977).
2. G. N. Abaev, E. K. Popov, et al., Dokl. Akad. Nauk SSSR, 259, No. 3, 655-660 (1981).
3. O. P. Klenov, Yu. Sh. Matros, et al., Teor. Osn. Khim. Tekh., 17, No. 3, 337-341 (1983).
4. E. K. Popov, "Study of the aerodynamics of nonuniformities in apparatus with fixed catalyzer beds,: Candidate's Dissertation, Technical Science, Yaroslav' (1980).
5. I. S. Luk'yanenko, Yu. I. Kuznetsov, et al., Teor. Osn. Khim. Tekh., 22, No. 3, 566-570 (1988).
6. V. N. Koleskin, Mechanics of Heterogeneous Media [in Russian], Yaroslav' (1986), pp. 46-56.
7. V. V. Klyuev, É. I. Vainberg, et al., Defektoskopiya, No. 3, 42-60 (1980).
8. V. I. Barakhov, I. P. Dimitrienko, et al., Inzh.-fiz. Zh., 51, No. 6, 1021-1027 (1986).
9. Yu. S. Zav'yalov, B. I. Krasov, and V. L. Miroshnichenko, Spline Function Methods [in Russian), Moscow (1980).