VALVE EFFECT IN A GRANULAR BED

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The appearance of a pronounced velocity-field nonuniformity beyond the granular bed has been established experimentally for the case in which a stream compresses the bed. This effect is absent in the opposite case, when the bed is made friable by a stream.

The nonuniformity of the stream beyond the catalyst bed in a chemical reactor was observed a rather long time ago [1, 2]. This subject was discussed at the conference on aerodynamics of chemical reactors in Novosibirsk (1975) [3] by Myasnikov [4], Abaev [3], and the authors of this article, who carried out the experimental investigations in 1966. This article presents the data explaining the mechanism of this phenomenon.

The experimental apparatus (Fig. 1) consists of a cylindrical channel 3, 40 mm in diameter. Air is supplied to the channel either from the top or from the bottom. A fine metallic or caprone screen 9 is mounted on its lower part, which supports the bed 8 of the height h. The delivery of air is measured by a Pitot tube 2, the static pressure take-off device 4 and a differential manometer 5. The velocity profile before the bed was measured with a thermoanemometer 7.

Copper balls with d = 1.5 mm, steel ball bearings with d = 1 mm, screened farina with a grain size d = 0.3 to 0.5 mm, and a powder consisting of nickel beads with d = 0.25-0.30 mm were used as fillers.

The velocity profile at the exit of the bed was measured by a Prandtl tube 10 or a thermoanemometer.

The experiments showed that when the air blast is directed downward and the velocity profile is uniform at the inlet, the velocity profile at the exit of the bed is highly nonuniform. This is shown in Fig. 2 where curves 1-3 represent the velocity profiles for various values of d at a constant value of h = 15 mm and the pressure before the bed $p_0 = 3 \cdot 10^5$ N/m^2. They have sharp maxima at the walls of the channel and a minimum at its axis. The ratio v_{max}/v_{min} reaches 7.

A similar nonuniformity is characteristic only of fillers consisting of loose, free-flowing particles. Blowing through screens and plates of porous graphite exhibited a uniform velocity profile at the outlet (curve 4). From this it follows, in particular, that the reason for nonuniformity at the exit cannot be the possible nonuniformity of the stream at the inlet to the bed. Nevertheless, in order to evaluate the effect of the inlet nonuniformity, the velocity profile was varied with the aid of diaphragms 11 (Fig. 1) and disks of various diameters. According to Lev [5], when the resistance coefficient of the grid $\xi > 2$, the grid must change the nonuniformity of the velocity profile. The resistance coefficient of a bed consisting of beads with d = 1 mm and h = 5 mm, calculated according to [6], equals 12.8. However, introduction of a disk, i.e., at the layer inlet creating a velocity profile with a maximum at the periphery and a dip at the axis does not cause a change of nonuniformity at the outlet of beds 15 and 5 mm thick. The same situation of nonuniformity is observed as in Fig. 2.

In forming the velocity profile at the bed inlet with the maximum in the center and the minimum (or even a counterflow) at the periphery with the aid of sufficiently small-diameter diaphragms, boiling develops in the upper part of the bed. In this case the bed is distinctly divided into the stationary central and boiling peripheral parts. Any further decrease of the diaphragm orifice leads to the increase of the boiling zone volume right up to the diaphragm, while a crater is formed in the stationary part.

In the experiments, the bed thickness in the center of the crater was reduced to 2 mm at the initial height of the filler of 10 mm. But even under these conditions, the flow character at the exit from the bed did not change.

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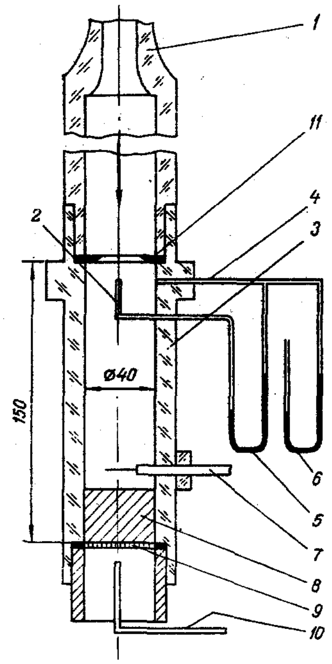

Fig. 1

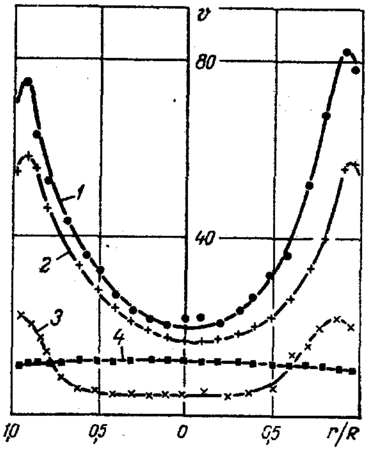

Fig. 2

Fig. 1. Experimental layout: 1) supply channel; 2) Pitot tube; 3) working channel; 4) static pressure take-off device; 5) differential manometer; 6) static pressure manometer; 7) thermoanemometer probe; 8) particle bed; 9) screen; 10) Prandtl tube; 11) diaphragm or disk.

Fig. 2. Velocity fields behind the granular bed: 1, 2, and 3, $p_0 = 3 \cdot 10^5$ N/m^2, h = 15 mm; 1) d = 1.5 mm, 2) d = 1 mm, 3) d = 0.3-0.5 mm; 4) graphite, $\varepsilon = 0.25$, h = 5 mm, $p_0 = 4 \cdot 10^5$ N/m^2.

It is well known [5] that near a solid wall, due to its regulating action, the structure of the granular bed is somewhat altered in comparison to the areas farther away from the wall. The size of the zone subject to the wall effect is on the order of several d. Therefore, it is a priori clear that nonuniformity at the wall cannot be the reason for the nonuniformity of the discussed velocity profile, the extent of which is determined by the size of the channel and is practically independent of the diameter of the particles as can be seen from Fig. 2. Nevertheless, in order to eliminate the porosity increase at the wall, experiments were set up in which the walls of the channel were lined with soft sheet-rubber and the beads were imbedded into the wall as a result of pressure. At the same time, the character of flow did not change. The shape of the channel cross section has also no effect on the nonuniformity character of the velocity profile. This was confirmed by special experiments in a channel with a rectangular 68 × 30 mm cross section.

In order to study the interaction of the bed with the screen we used an apparatus consisting of a rectangular column with 150 × 340 mm cross section, 600 mm high, filled half-way with balls (d = 36 mm), and restricted at the top and at the bottom with rigid grids from the same kind of balls. Air was blown through the bed of balls from the bottom toward the top and the pressure drop in the bed, the air consumption, and the height of the bed were measured. The coefficient of bed resistance ξ was determined from these data. When the velocity of filtration reached the velocity of hovering, the balls were lifted and "stuck" to the upper grid. At the same time, a possibility arose to again significantly reduce the air consumption and to obtain the upper grid at the same parameters as for the rigid filling on the lower grid. The resistance coefficient of the bed pressed against the upper grid turned out to be in all cases significantly higher than for the bed on the lower grid, whereupon it was higher the slower the balls were lifted. In order to find a maximum in a bed restricted at the top, the upper and the lower grids were drawn together in such a way that room for only one ball remained between them. Each ball in the interior row was capable of being displaced upward by about 1 mm, whereupon the number of balls in the "free" bed was equal to the number of spaces between the balls in the upper grid. The dependence of the resistance coefficient of such a bed on Reynolds number is shown in Fig. 3

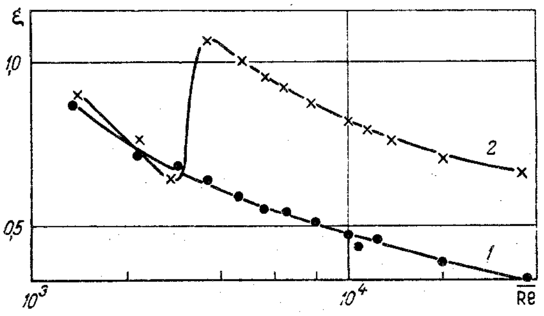

Fig. 3. Experimental data on valve effect.

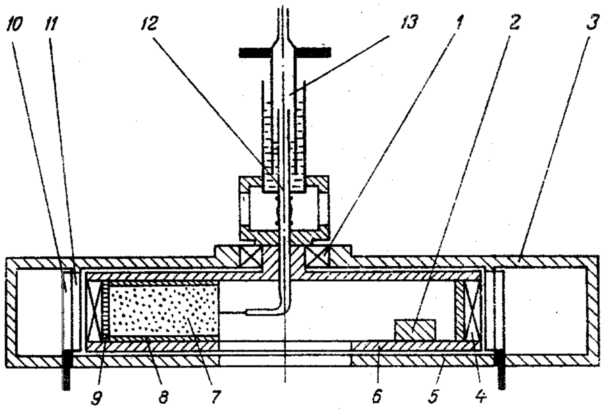

Fig. 4. Experimental layout: 1) bearing; 2) counterweight; 3) distributing helix; 4) blades; 5) housing; 6) rotating chamber; 7) particle bed; 8) working channel; 9) screen; 10) adjusting ring; 11) deflector; 12) Pitot tube; 13) liquid seal.

(curve 2). The sharp jump of the resistance indicates the closing of passages in the upper grid. For comparison, Fig. 3 presents the resistance coefficient of the same bed, but rigidly fastened between the grids with the help of knitting needles (curve 1).

This way the free balls adhering to the upper grid act very much like valves.

This leads to the conclusion that the flow in the bed must vary depending on whether the bed is compressed by the stream or becomes porous as, for example, in the case of blowing through from the bottom. The comparison of experimental results in the very same bed, 61 mm high, consisting of particles with d = 0.25-0.3 mm, with the same excess pressure, with various directions of the stream, shows that when the bed is compressed, the tendency to form a typical nonuniformity is observed. However, this nonuniformity is considerably weaker than that of Fig. 2, which is associated with a substantially lower pressure. The excess pressure was only $3 \cdot 10^3$ N/m^2, because when it was increased, the bed, which was purged from the bottom, started to boil.

In order to achieve the same stream parameters as in the first series of experiments, an attempt was made to restrain the bed, which was purged from the bottom and consisted of steel particles, through the use of a magnetic field. To do this, pipe 3 was wound with a current-carrying winding. This attempt, however, did not succeed due to the fact that the magnetic field exerted a strong regulating effect on the particles which disturbed the structure of the bed.

Therefore, an apparatus was constructed in which the function of the force of gravity necessary for the support of the bed was carried out by centrifugal force (Fig. 4). The apparatus consists of a housing 5 in which a rotating cylindrical chamber 6 equipped with blades 4, is suspended on bearing 1. The chamber contains a radially arranged, cylindrical working channel 8 the outside face of which, covered with screen 9, is placed into an opening in the side surface of the chamber impermeable in the rest of its parts. The air enters the distributing helix 3, passes through the deflector 11 regulated by the rotating ring 10 into the working channel 8, filters through the particle bed 7, and exits downward through the central opening. The stream, involuted by the deflector 11, rotates chamber 6 with the working section 8 through the action of the blades 4, the weight 2 serves as a counterweight.

The measurements were carried out by the rotating Pitot tube 12, the impulse line of which is connected with the liquid seal 13. The particle bed was filled in advance into the working channel and was additionally supported by a screen placed on the inner face. The diameter of the working channel was 75 mm. The measurements of the velocity field behind the bed, which was 80 mm thick and consisted of particles with a diameter d = 1.5 mm, showed only minor nonuniformity connected with the wall proximity effect; the large scale nonuniformity disappeared.

All of the presented data point to the fact that the reason for nonuniformity of the velocity field is the nonuniform stressed state of the bed itself. The bed is compressed by the stream, the grid and the walls, whereupon the latter eliminate the possibility of the particle displacement. Deep within the bed the particles become freer, and under the action of the stream strive to decrease the size of the passages, thus closing off the central part of the bed. Inasmuch as the stressed state of the bed nearly does not depend on the size of the particles that compose it, but is determined by the geometry and the acting forces, the characteristic scale of nonuniformity is the size of the channel.

The considerations presented here have, of course, a purely qualitative character and the theory of the stressed state of the bed is yet to be worked out.

NOTATION

d	is the particle diameter;
h	is the height of the bed;
p_0	is the pressure before the bed;
v	is the flow velocity;
ξ	is the bed resistance coefficient;
Re	is the Reynolds number;
ε	is the porosity;

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