We have also investigated hydraulic resistance in curved bends. For bends with a radius of curvature $R/D > 4$, no marked influence of curvature on the resistance could be found. Under these conditions, the regime of material movement was not disrupted. With a bend with $R/D = 2$, the experimental values of pressure loss proved to be about twice as high as those calculated from the formula for a straight section of the same length. Thus, it is advisable to avoid the use of bends with radius less than $R/D = 4$.

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EXPANSION AND LIMITING HEIGHT OF INJECTOR BED

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In contacting solid particles in the suspended state with gases, there is considerable interest in the injector bed [1], the basic properties of which are governed by the high (transsonic) efflux velocities from the distributor grid, along with moderate velocities above the bed (including velocities lower than the initial fluidization velocity). Owing to the high velocity heads in the gas medium, in accordance with Bernoulli's equation, low-pressure zones are created. Solid particles tend to move into these zones from the sections located between jets, where the pressure is somewhat lower; the particles are captured by the gas jets and are moved upward. In a correctly organized injector bed, there are no stagnant zones; the gas flow is very nearly uniformly distributed throughout the cross section of the bed, and the mixing of the solid particles is near ideal.

The considerable different in velocities of the phases near the grid leads to a sharp intensification of mass transfer. For example, when drying a moist disperse material containing free water, the phenomenon of mechanical stripping of water from the particle surface is observed. This permits the removal of considerable quantities of water without the expenditure of energy in vaporizing the water.

In using an injector bed, it is important to know the limits of existence of the system and its hydrodynamic characteristics. Certain properties of the injector bed have been described previously [1]. The objects of investigation in the present work have been the limiting height and expansion of the system under study.

The test vessel, with a diameter of 180 mm and 2000 mm,* was fitted with a perforated grid, in the openings of which there were mounted Laval nozzles with a narrow-section diameter of 1.0 mm and a wide-section (upper) diameter of 1.27 mm, or cylindrical nozzles with diameter of 1.5, 2, 3, or 5 mm. The number of openings in each grid was selected so that the open area would be 0.25%; this means that for the five nozzles indicated above, the respective spacings of the grid openings were t = 20, 25, 31, 47, and 75 mm; and the respective numbers of openings were n = 80, 58, 33, 15, and 5. The experiments were conducted with polycaproamide granules with equivalent diameter (weight average) $d_e = 1.25$, 2.2, and 4.5 mm and density $\gamma_s = 1200$ kg/m^3. The polymer granules with the indicated equivalent diameters were, respectively, cylinders with a diameter of 0.66 mm and a length of 3.2 mm, and elliptical cylinders in two different sizes, the smaller with

*As in Russian original; presumably the vessel is 180 mm in diameter and 2000 mm in height — Translator.

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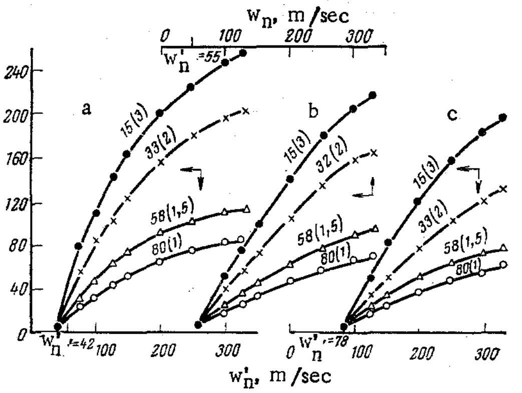

Fig. 1. Limiting height of injector bed H_{lim} as a function of velocity of fluidizing agent in nozzles w_n. Numbers on curves indicate number of nozzles in grid; numbers in parentheses indicate nozzle diameter in mm. Particle size d_e in mm as follows: a) 1.25 mm; b) 2.2 mm; c) 4.5 mm.

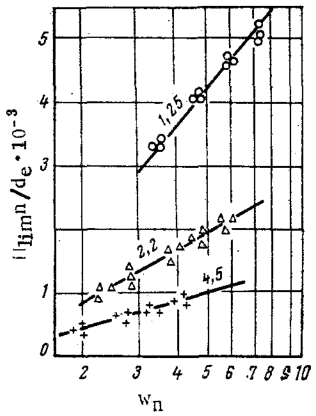

Fig. 2. Function $H_{lim}n/d_e = f(w_n)$. Numbers on curves indicate particle in size d_e, mm.

with semiaxes 1.4 ×1.1 mm and length 2 mm, the larger with semiaxes 3.5 × 2.5 mm and length 4 mm. Air was used as the injected agent, the flow rate varying in the course of the experiments from 15 to 170 mm^3/h* (velocity at nozzle exit w_n from 40 to 450 m/sec).

Limiting Height of Bed. It was established through preliminary experiments that an injector bed can be realized only when the height of the original (undisturbed) bed does not exceed a certain limiting value H_{lim} that depends on the properties of the solid particles and the injecting agent, the velocity of the injecting agent, and the geometric characteristics of the grid. With an undisturbed bed height $H_0 > H_{lim}$, injection is not observed; several (three to eight) focal zones (spouts) are formed in the bed; the main mass of particles, relatively unfluidized, remains in the zones between the spouts.

In performing the experiments, the required air rate was established, and, with the particular solid particles and grid being tested, the limiting bed height H_{lim} was determined through visual observation of the moment at which the injector bed degenerated. The experimentally determined values of H_{lim} are shown in Fig. 1.

An analysis of these results shows that, regardless of which grid is used, extrapolations of the curves for H_{lim} vs w_n to the level $H_{lim} = d_e$ will lead to identical values of w'_n, as indicated on the curves. It can be seen that H_{lim} increases with increasing w_n, at first rapidly and then more slowly. For identical relative velocities $w_n = w_n/w'_n$,† the corresponding values of H_{lim} are very nearly identical.

An increase in the spacing t, while holding the percentage open area of the grid at a constant level, leads to an increase in limiting height of the injector bed; this is explained by the accompanying increase in kinetic energy of a single jet, which increases its carrying capacity. However, when t is increased beyond a certain maximum, the injector bed degenerates into a relatively unfluidized bed with individual spouts, the same as when $H_0 > H_{lim}$. Under the conditions of these particular experiments, this limiting value of t is 45-50 mm, i.e., 16-20 cm^2 of cross-sectional area of the grid per opening; with n = 5, the injector bed degenerates.

*As in Russian original.

† As in Russian original, the symbol w_n is used for both absolute and relative velocities later in the article — Translator.

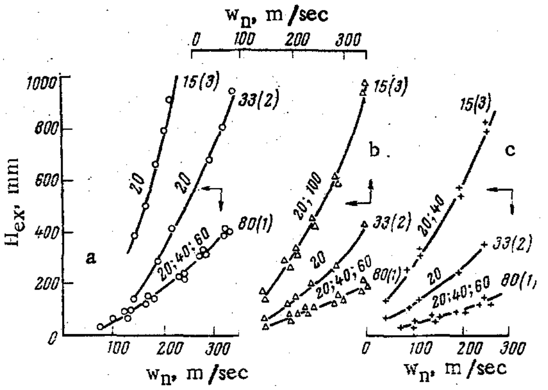

Fig. 3. Influence of injecting-agent velocity on bed expansion. Numbers to the right of curves indicate nozzle diameter in mm; numbers to left of curves indicate height of undisturbed bed H_0 in mm. Particle size d_e in mm as follows: a) 1.25; b) 2.2; c) 4.5.

In correlating the experimental data (see Fig. 1), it was first necessary to determine the initial velocity w'_n. With the flow around the solid particles near the grid known to be turbulent in character (sufficiently large particles, high gas velocities), we can assume [2] proportionality between the Reynolds number $Re'_n = w'_n = w'_n \cdot d_e \gamma/\nu$ and the square root of the Archimedes number

$$Ar = \frac{g \cdot d_e^3}{\nu^2} \cdot \frac{\gamma_s - \gamma}{\gamma},$$

where ν and γ are the viscosity and density of the gas. With numerical coefficients in the range $Ar = 6 \cdot 10^4$ to $3 \cdot 10^6$, we have

$$Re'_n = 10 \cdot \sqrt{Ar}. \quad (1)$$

The dependence of H_{lim} on w_n is linear when the experimental data are plotted on semilogarithmic coordinates of $H_{lim}n/d_e$ vs $\log w_n$ within the limits of each particle size (Fig. 2).

The experimental data shown in Figs. 1 and 2 can be approximated by a general empirical relation that has been verified for $w_n = 1.5$–8:*

$$\frac{H_{lim}}{d_e} = 2.1 \cdot 10^5 \cdot Ar^{0.33} \lg w_n \frac{1}{n}. \quad (2)$$

The average deviation of the experimental data from the correlation equation (2) is 6.5%, with a maximum deviation of no greater than 9%.

The relation (2) was obtained on the basis of experiments in a vessel with a diameter D = 180 mm. It is probable that, in making the transition to vessels with other diameters, the system will be modeled by holding constant the cross-sectional area [of the vessel] per opening, i.e., D^2/n = idem.

Expansion of Bed. An injector bed, in contrast to a normal fluidized bed, does not form inhomogeneous systems with gas bubbles, the void fraction of which is usually greater than 0.7–0.8, and the solid particles are a discrete phase from the very start. Only at a high expansion ratio will the concentration of particles at and near the free surface of the bed be greater than the concentrations in the other parts of the bed. If a polydisperse mixture is used in an injector bed, no separation of particles according to size or density is observed.

The height of the expanded bed H_{ex} under various operating conditions was determined visually. The influence of the velocity of air leaving the nozzle w_n on the expansion of the injector bed is illustrated in Fig. 3. As would be expected, H_{ex} increases with increasing w_n; here H_{ex} is independent of the height of undisturbed bed H_0 (with H_0 ranging from 10 to 100 mm) but increases with increasing kinetic energy of the individual jet, i.e., with decreasing number of openings in the grid and correspondingly larger openings.

In studying the expension of the injector bed, we may examine the equilibrium forces acting on a solid spherical particle moving in a single jet of gas (or liquid). In the general case [3],

*As in Russian original; probably intended to refer to relative velocity w_n/w'_n (as in Fig. 2) rather than to absolute nozzle velocity (as in Fig. 1) — Translator.

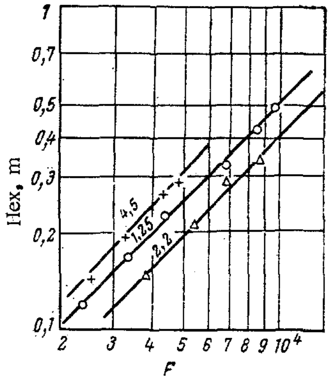

Fig. 4. Expansion of injector beds of particles of different sizes. Numbers on curves indicate particle size d_e in mm.

where

$$\frac{\partial u}{\partial \tau} = -g\left(1-\frac{\gamma}{\gamma_s}\right) + \frac{18\cdot\nu\cdot\gamma}{d_e^2\cdot\gamma_s}(w-u) + \frac{3\gamma}{\gamma_s\cdot d_e}(w-u)^2, \tag{3}$$

where w and u are the velocities of the gas through the particle.

Neglecting the laminar component, i.e., the second term in the right-hand side of Eq. (3), and replacing the time τ by a vertical coordinate z, and the particle velocity $u \left[\frac{\partial u}{\partial \tau} = \frac{u\,du}{\partial z}\right]$, we obtain by means of scale transformations, with $\gamma \ll \gamma_s$, the following comparison:

$$\frac{u^2}{z} \simeq g \simeq \frac{\gamma (w-u)^2}{\gamma_s \cdot d_e}. \tag{4}$$

Whence, by the usual procedure, we form dimensionless groups characterizing the process of particle rise (or, as an end result, expansion of the injector bed). Of these groups for describing the bed expansion, the most interesting proved to be the group $\gamma(w-u)^2/\gamma_s g d_e$, which for the case under consideration in the initial zones of the jet ($z \to 0$ and $u \to 0$, or at least $u \ll w_n$) assumes the form $F = \gamma w_n^2/\gamma_s g d_e$. This group was used as the basis for treating the experimental data on expansion of the injector bed.

As can be seen from Fig. 4, where the experimental data are shown for n = 80, 33, and 15, the curves for bed expansion, as the transition is made from fine to coarse particles, are arranged in anomalous order. The explanation for this anomaly is the difference in shape and size among the three types of particles used in this study. The influence of shape is generally taken into account [4-6] through hydrodynamic shape factors ξ for the particles. As such a factor in the present study, we selected the ratio of the length of the flow path around the particle l [6] to the equivalent diameter of the particle, $\xi = l/d_e$.

It is known [5] that, for the case of turbulent flow around a particle, the particle is oriented with its greatest cross section normal to the flow. This means that the particles (in a rising flow) will be oriented so as to maximize the horizontal midsection for each particle. From the geometric dimensions of the particles, it is not difficult to obtain the values of l and to calculate the value of ξ. For the particles used in this study, with sizes (equivalent diameters) of 1.25, 2.2, and 4.5 mm, the respective values of ξ are 0.83, 1.8, and 2.2.

The experimental data on bed expansion were represented in the form of a relation of the dimensionless groups $\xi H_{ex} n/d_e$ and F,

$$\xi \frac{H_{ex}\cdot n}{d_e} = 2.1F. \tag{5}$$

This relation approximates the experimental data with an average error of 12%. In view of the relatively low accuracy of the visual observations, such a deviation cannot be regarded as significant or serious.

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