LONGITUDINAL MIXING (EFFICIENT DIFFUSION) OF THE SOLID PHASE IN A FLUIDIZED BED WITH AVERAGE-BULK PACKING

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A nonstationary technique is used to study longitudinal mixing of a solid phase in a fluidized bed with packing consisting of spheres, Rashig rings, and others. As a result of the correlation of experimental data, an expression is obtained for computations.

There exist data concerning the behavior of the transport of the solid phase in a fluidized bed with low-bulk packing [1], occupying less than 7% of the layer volume. At the same time, for processes occurring in aggressive media as well as for adsorption processes, packings in the form of filling material consisting of elements with volumes that constitute 10-50% of the layer volume — spheres, Rashig rings, and others — are promising.

Information concerning the coefficients of longitudinal diffusion of heat (mass) in a fluidized bed with packing consisting of spheres, obtained by different methods, is contained in [2-6]. The authors of [2, 3] used a nonstationary tracer technique. In [2], mixing of copper particles was examined. The tracer particles consisted of nickel particles that have a density equal to the density of copper. The measurement of the concentration of nickel particles was based on the use of magnetic properties. In [3], mixing of glass particles and a cracking catalyzer were studied. The particles were tagged chemically or were colored.

A stationary heat technique was used in [4-6] for measuring the effective thermal conductivity of a fluidized system. Particles of corundum and aluminum oxide were fluidized. In [6], cylindrical tablets were used as packing; the temperature in the bed was maintained approximately equal to 800°C.

Packings consisting of Rashig rings and their modifications are of interest [7]. In comparison with spherical packing, they have a large effective volume and result in less deposition of the fluidized particles on the packing elements. There are no data on longitudinal mixing of the solid phase in a fluidized bed with packing consisting of Rashig rings and their modifications.

The purpose of the present work is to obtain experimental data on longitudinal mixing of the solid phase in a fluidized bed with the types of packing indicated and to elucidate the behavior of the transport of the solid phase in such a system.

In order to determine the coefficient of longitudinal mixing, we use the nonstationary technique presented in [2]. Initially, the fluidized bed was separated into two equal parts, in which one part (usually the lower one) contained moistened particles and the other contained dry material. The variation in the concentration of moistened particles with time and height in the fluidized bed can be found by solving the diffusion equation $\partial a/\partial\tau = D_S\partial^2 a/\partial h^2$ with the following initial boundary conditions, corresponding to the conditions of the experiments:

$$\text{for}\quad \tau = 0 \ \text{and}\ h = 0 - H/2 \quad a = a_0,$$
$$h = H/2 - H \quad a = 0;$$
$$\text{for}\quad h = 0 \ \text{and}\ h = H \quad da/dh = 0.$$

The solution to this problem is presented, e.g., in [8] in the form of a function $a/a_0 = f(h/H, \mathrm{Fo})$. Using this function, the values of a/a_0 were computed from the experimental values of τ measured at time D_S.

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TABLE 1. Characteristics of Fluidized Particles

d, mm	u_0, cm/sec	ρ_s, kg/m³	Ga
0,19	2,0	1300	0,32
0,32	2,0	900	1,3
0,55	6,5	900	6,5

TABLE 2. Characteristics of Packing

Type of packing	Dimensions of packing elements, cm	ε_p	l_p
Spheres	$D_{sp}=1,1$	0,43	0,1
Spheres	$D_{sp}=1,3$	0,43	0,15
Spheres	$D_{sp}=3,8$	0,49	0,61
Rashig rings	2,5×2,5×0,45	0,67	0,38
Rings with slits	2,2×2,3×0,5	0,68	0,29
Modified Rashig rings	3×3×3	0,68	0,5

The moisture content of the particles was measured by a hygrothermal equilibrium method [9] in the settled bed after the fluidizing air is no longer introduced. The measurements were carried out in four sections of the bed with h/H = 0; 0.3; 0.7; and 1. In each of the indicated sections samples of air were extracted at several points. The air samples were analyzed with the help of coulometric moisture sensors [9] to within ±5%. The moisture content of air extracted from the intergranular channels corresponded to the average equilibrium moisture content of particles located in a radius of the order of 1 cm from the point of extraction.

Experiments were carried out in columns with diameters of 15 and 30 cm. Silica gel particles with three sizes and different densities were fluidized. The characteristics of the fluidized materials are presented in Table 1. The packing consisted of spheres, ceramic Rashig rings, rings with slits and modified Rashig rings. Their geometrical properties are presented in Table 2. The height of the settled layer varied in the range 30–120 cm; the filtration rate varied from u_0 to 40 cm/sec. The conditions of our experiments, as well as the experiments of other work, are presented in Table 3. In all, about 250 tests were conducted.

From physical considerations, it may be expected that the coefficient of longitudinal mixing depends on the following parameters:

$$D_s = f(\rho_s, \rho, \nu, g, d, u, \varepsilon_p, l_p, D_c, H_0). \tag{2}$$

In accordance with the π-theorem from the theory of similarity, the following seven dimensionless complexes can be formed from the parameters indicated:

$$\frac{D_s}{H_0(u/\varepsilon_p - u_0)},\ \mathrm{Fr},\ \mathrm{Ga},\ \frac{\rho}{\rho_s},\ \frac{l_p}{d},\ \frac{H_0}{l_p},\ \frac{D_c}{l_p}.$$

Here, the determining velocity of the fluidizing gas is taken as the excess velocity in the section of the column not occupied by packing elements, $u/\varepsilon_p - u_0$. Using the complexes indicated, the dependence sought (2) can be represented in the form of the following power law function:

$$\frac{D_s}{H_0(u/\varepsilon_p - u_0)} = a_0 \mathrm{Fr}^{a_1} \mathrm{Ga}^{a_2} \left(\frac{\rho}{\rho_s}\right)^{a_3} \left(\frac{l_p}{d}\right)^{a_4} \left(\frac{H_0}{l_p}\right)^{a_5} \left(\frac{D_c}{l_p}\right)^{a_6}. \tag{3}$$

The values of all the powers a_i (i = 1–6), the coefficient a_0, the standard deviation of the powers σ_i and their confidence intervals were obtained by analyzing our data and the experimental material from [2–6] (Table 3) using the method of least squares. The significance level was taken as 5%. The calculation was carried out on a computer using the program described in [10]. The results of the calculation are presented in Table 4.

It is evident from Table 4 that the exponents a_1, a_4, a_5, and a_6 equal zero, since the confidence limits of these exponents exceed their actual values. For this reason, the

TABLE 3. Conditions for Experiments on Mixing

Notation on Fig. 1	Material	d,mm	Type of packing	Packing dimensions, cm	H_0, cm	D_c,cm	Reference
1	Silica gel	0,32	Rashig rings	2,5×2,5×0,45	30	15	
2	»	0,32	»	2,5×2,5×0,45	30	30	
3	»	0,32	»	2,5×2,5×0,45	60	15	
4	»	0,32	»	2,5×2,5×0,45	60	30	
5	»	0,32	»	2,5×2,5×0,45	90	15	
6	»	0,32	»	2,5×2,5×0,45	90	30	
7	»	0,32	Spheres	$D_{sp}=1,3$	30	15	
8	»	0,32	»	»	60	15	
9	»	0,32	»	»	90	15	
10	»	0,19	»	$D_{sp}=1,1$	30	15	
11	»	0,32	»	$D_{sp}=3,8$	60	30	
12	»	0,32	Rings with slits	2,2×2,3×0,5	30	15	
13	»	0,32	»	2,2×2,3×0,5	60	15	
14	»	0,55	»	2,2×2,3×0,5	60	15	
15	»	0,32	Modified Rashig rings	3×3×3	60	15	
16	»	0,32	The same	3×3×3	60	30	
17	»	0,32	»	3×3×3	120	30	
18	Copper	0,1	Spheres	D_{sp}—0,95	61	5,1	[2]
19	»	0,1	»	»	41	5,1	[2]
20	»	0,1	»	»	20	5,1	[2]
21	»	0,14	»	»	61	5,1	[2]
22	»	0,14	»	»	41	5,1	[2]
23	»	0,36	»	»	20	5,1	[2]
24	»	0,36	»	»	61	5,1	[2]
25	»	0,1	»	$D_{sp}=1,27$	20	5,1	[2]
26	»	0,14	»	$D_{sp}=0,95$	41	5,1	[2]
27	»	0,14	»	$D_{sp}=0,66$	41	5,1	[2]
28	Catalyzer	0,13	»	$D_{sp}=1,25$	50	8	[3]
29	Glass	0,063	»	»	50	8	[3]
30	Catalyzer	0,053	»	»	50	8	[3]
31	»	0,053	»	$D_{sp}=2,42$	50	8	[3]
32	»	0,058	»	$D_{sp}=1,25$	50	8	[3]
33	Corundum	0,32	»	$D_{sp}=1,5$	50	11	[4]
34	»	0,12	»	»	50	11	[4]
35	»	0,12	»	D_{sp}—0,7	50	11	[4]
36	»	0,32	»	$D_{sp}=1,2$	50	11	[4]
37	»	0,12	»	»	50	11	[4]
38	»	0,32	»	$D_{sp}=4,4$	130	40×27	[5]
39	»	0,63	»	»	130	40×27	[5]
40	»	0,25	Cylindrical tablets	1,1×1,2	50	18	[6]

TABLE 4. Numerical Values of a_0 – a_6 from Eq. (2), Their Mean-Square Deviations σ_i, and the Confidence Intervals $t\sigma_i$

i	a_i	σ_i	$\pm t\sigma_i$
0	1,585	—	—
1	0,0063	0,03	0,06
2	–0,163	0,037	0,074
3	0,58	0,07	0,14
4	0,123	0,145	0,29
5	–0,226	0,1	0,2
6	–0,057	0,14	0,28

cofactors

$$\mathrm{Fr}^{a_1},\ \left(\frac{l_p}{d_s}\right)^{a_4},\ \left(\frac{H_0}{l_p}\right)^{a_5} \text{ and } \left(\frac{D_c}{l_p}\right)^{a_6}$$

can be omitted. Finally, we obtain

$$\frac{D_s}{H_0\,(u/\varepsilon_p - u_0)} = 0{,}45\mathrm{Ga}^{-0.16}\left(\frac{\rho}{\rho_s}\right)^{0.58}. \tag{4}$$

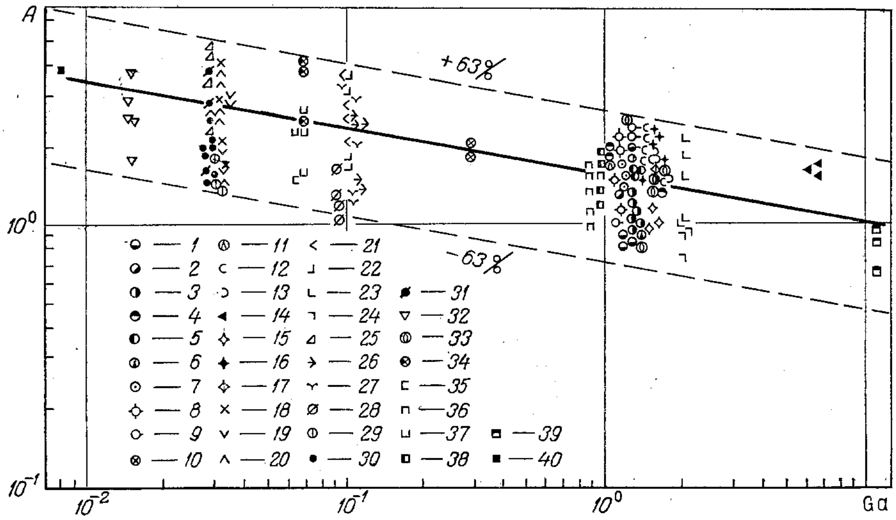

Fig. 1. The function $A = f(Ga)$, where $A = [D_s/H_0(u/\varepsilon_p - u_0)] \cdot (\rho_s/\rho)^{0.58}$.

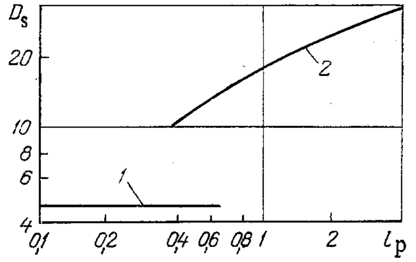

Fig. 2. Comparison of the coefficients of longitudinal mixing in fluidized beds with average- and low-bulk packing with $d = 0.15$ mm, $\rho_s/\rho = 2200$, $u - u_0 = 10$ cm/sec: 1) calculation using (4) with $\varepsilon_p = 0.7$; 2) calculation according to [1].

This general function is illustrated in Fig. 1, wherein all experimental points are also indicated.

The weighted mean error of the approximation is ±63%. Formula (4) is applicable for the following ranges of the determining parameters: $d = 0.058$–0.63 mm; $H_0 = 20$–120 cm; $D_c = 4.3$–45 cm; $l_p = 0.1$–0.61 cm; $Ga = 0.7 \cdot 10^{-2}$–11; $Fr = 10^{-5}$–2; $\rho_s/\rho = (0.7$–$12) \cdot 10^3$.

The function (4) obtained above correlates the data of different researchers, measured by different techniques under various conditions, and encompasses a large quantity of experimentally measured points. A feature of the reliability of the proposed approximation (4) is the confidence interval for the center of the field of experimental points. The magnitude of this confidence interval, computed according to the weighted mean error in the approximation and the number of experimental points, is ±9% with a confidence probability of 95%. Thus, the approximation (4) gives a quite reliable representation of the transport properties of the solid phase in the system being studied.

As an example, in Fig. 2, D_s is shown as a function of l_p from (4) and from similar formulas for low-bulk packing from [1]. The calculation was carried out with $H_0 = 30$ cm, $\rho_s/\rho = 2200$, $d = 0.15$ mm ($\varepsilon_p = 0.7$ for packing with average bulk). It is evident that for the same excess velocity $u - u_0$, computed for the total section of the column, the intensity in the fluidized bed with average-bulk packing is approximately 2 times less than in the layer with low-bulk packing. Thus, with the help of average-bulk packing, it is possible to decrease the mixing of the solid phase to a larger extent than with the help of low-bulk packing.

It follows from formula (4) that the height of the settled bed and velocity of the gas have the greatest effect on D_s. The coefficient of longitudinal mixing is proportional to the height of the settled bed H_0. Such a dependence of D_s on H_0 is probably related to the increase in the scale of circulating fluxes of solid material with the increase in the height of the settled bed.

It also follows from (4) that mixing in the fluidized bed with average-bulk packing does not depend on the diameter of the apparatus. The data concern an apparatus with a diameter less than 0.5 m. Taking into account the fact that in a fluidized bed with low-bulk packing the coefficient of longitudinal mixing depends weakly on D_c for $D_c \leqslant 0.7$ m [1], it may be expected that the computational formula (4) is also applicable for $D_c > 0.5$ m. This opens up the possibility of using (4) for calculating commercial installations, e.g., adsorbers with a fluidized bed [11], the operation of which, to a large extent, is determined by the longitudinal mixing of fluidized adsorbent particles [12].

NOTATION

D_s, coefficient of longitudinal mixing (effective diffusion) of the solid phase, cm²/sec; a, moisture concentration in solid particles, kg/m³; ρ_s, apparent density of the fluidized particles, kg/m³; d, average diameter of the fluidized particles, mm; h, H_0, and H, instantaneous, initial, and overall height of the fluidized bed, cm; D_c, diameter of the column, cm; u_0, incipient fluidization rate, cm/sec; u, filtration rate, cm/sec; ρ, gas density, kg/m³; ν, gas viscosity, cm²/sec; g, acceleration of gravity, cm/sec²; D_{sp}, diameter of the spheres, cm; $l_p = (V - V_p)/S_p$, hydraulic size of the packing, cm; V, volume of the bed with the packing, cm^{-3}; V_p, packing volume, cm³; S_p, surface area of the packing with volume V, cm²; ε_p, packing porosity; τ, time, sec; $Fo = D_s\tau/H^2$, Fourier number; $Fr = (u/\varepsilon_p - u_0)^2/gH_0$, Froude number; $Ga = d^3g/\nu^2$, Galilean number.

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