PARTICLE TRANSFER AND EXTERNAL HEAT EXCHANGE IN THE SPACE ABOVE A POLYDISPERSE FLUIDIZED BED

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The entrainment of particles from a polydisperse fluidized bed in a column 0.7 m in diameter with a bubble-cap gas distributor is investigated. Test data on external heat exchange in the space above the bed are obtained and generalized.

Investigations of the laws of heat and mass transfer in the space above a polydisperse fluidized bed are of great practical importance for the optimization of the construction of apparatus containing a fluidized bed in which the space above the bed occupies up to 80-90% of the working volume [1].

Particle entrainment from a fluidized bed has been studied in a number of papers. The results of this research were analyzed in the monographs [1, 2], where the following features were noted: The work was done, as a rule, in small installations with narrow-fraction disperse materials. Only in [3] was entrainment studied in an industrial-test installation with a grating area of 3 m^2. A similar situation is also characteristic for research on external heat exchange in the space above a bed: The very limited number of papers on this question [4-6] are devoted mainly to the investigation of heat exhange of fine ($d < 1$ mm) narrow-fraction particles in small apparatus. In this connection, the goal set before the present work was to study the laws of particle removal and external heat exchange in the space above a fluidized bed of large polydisperse particles in an apparatus of sufficiently large size.

The experiments were conducted on an installation 0.7 m in diameter with a bubble-cap gas-distribution grid (see [7] for a more detailed description of the installation). Samples of disperse material from the space above the bed were taken with a sampler consisting of a system of small "buckets" located at different levels. The time for one test was chosen empirically from the condition that the lower "bucket" was not able to overflow, and it ranged from 5 to 40 min. The coefficient of external heat exchange was determined by the steady-state method. The sensor consisted of a copper cylinder 30 mm in diameter with a wall thickness of 5 mm, inside which an electric heater was placed. A positioner enabled us to shift the horizontally placed sensor to different heights in the space above the bed and move it in the horizontal plane. Agloporit of a wide fractional composition (Fig. 1) was used as the disperse material. The density and porosity of the stationary filling and the velocity of minimum fluidization of the entire bed were $\rho_s = 1640$ kg/m³, $\varepsilon_0 = 0.40$, and $u_0 = 1.05$ m/sec. Fluidization was accomplished with air at a temperature of 15-20°C.

The difference in the concentrations of particles with a diameter greater than 0.63 mm and the remaining fine particles is clearly seen in Fig. 2. The critical size of the particles (d_c) was determined from their lower velocity, equal to the velocity of air filtration, from the Todes formula [1]

$$\mathrm{Re}_c = \frac{\mathrm{Ar}}{18 + 0{,}6\sqrt{\mathrm{Ar}}}. \tag{1}$$

The indicated difference in the concentrations of relatively large particles and fine ones with a diemater close to the critical particle size was also observed for all the other filtration velocities. It can be explained by the different mechanisms of entrainment of fine and large particles from a fluidized bed [2]. Large particles are thrown up randomly by bubbles in the form of "packets," after which they fall back. Therefore, their concentration in the space above the bed decreases by a "natural" exponential law. But the entrainment of fine particles from the bed, the hover velocity of which is close to the velocity of

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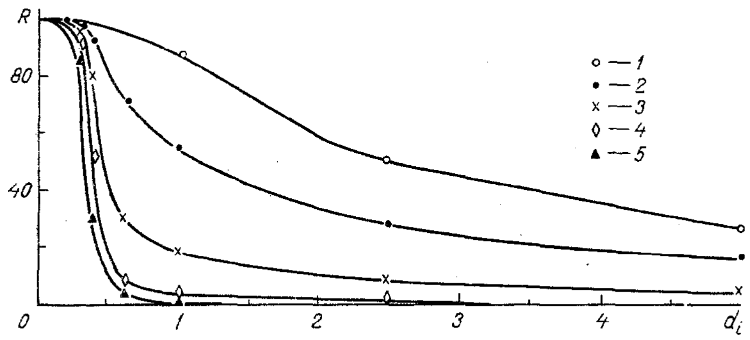

Fig. 1. Fractional composition of particles in the space above the bed (H_0 = 0.37 m; u = 1.8 m/sec): 1) bed material; 2) h = 0.84 m; 3) 1.34; 4) 1.84; 5) 2.14 m. R, %; d_i, mm.

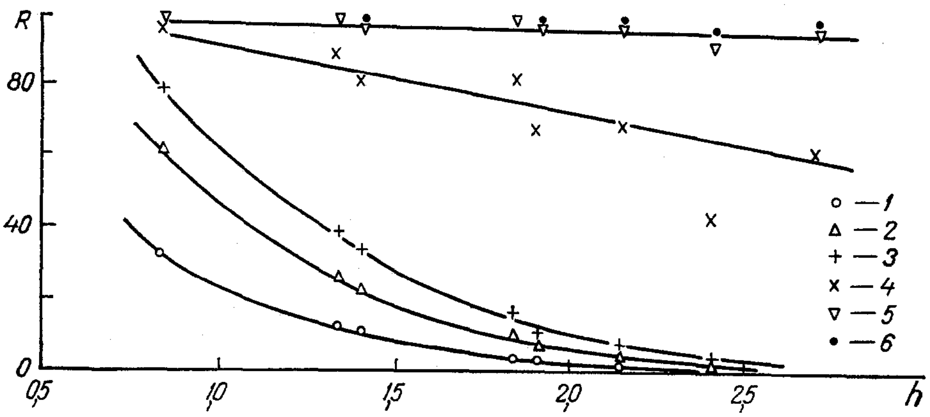

Fig. 2. Variation of the content of fractions over the height of the space above the bed (H_0 = 0.4 m; u = 2.1 m/sec; d_c = 0.33 mm): 1) d_i = 2.5 mm; 2) 1.0; 3) 0.63; 4) 0.40; 5) 0.315; 6) 0.20 mm. h, m.

gas filtration in the column, occurs predominantly by pneumatic transport, and their content over the height decreases by a nearly linear law (Fig. 2). The latter served as the basis for the development in [3] of a method of calculating the critical height of the separation zone (H_c), which was determined from the point of intersection with the abscissa axis of the extrapolated straight-line dependence of the content of fine fractions. For the data given in Fig. 2, H_c found in this way is ~6.0 m, which agrees well with the results of [3].

The masses of disperse material collected in the "buckets" per minute are shown in Fig. 3 as a function of height in the space above the bed. The quantity j characterizes the descending flux of particles and is directly connected with the particle concentration above the bed, which descreases exponentially with height. A generalization of the results obtained is shown in Fig. 4. The test data are described with a root-mean-square deviation of 18% by the function

$$\frac{j}{\rho_s u_0 S} = 1{,}75\cdot 10^{-3}\left(\frac{u-u_0}{u_0}\right)^{1{,}8}\exp(-1{,}2h/H_0). \qquad (2)$$

Values of the coefficient of external heat exchange in the space above the bed are shown in Fig. 5. The coefficient of heat exchange increases rather sharply with an increase in air velocity in regions adjacent to the upper boundary of the fluidized bed, which is explained by the considerable increase in particle concentration in this zone (see Fig. 3). With an increase of positional height of the sensor, the variation of α as the filtration velocity increases is smoother. Figure 5b indicates that some nonuniformity of gas distribution remains even in the space above the bed. At h = 1 m the velocity profile is leveled out and the values of α measured at different points of a horizontal cross section of the column hardly differ from each other. In Fig. 5a we give the dependence of α on the filtration velocity for pure air, constructed from the well-known Joukowski formula [8], which in our case is reduced to the form

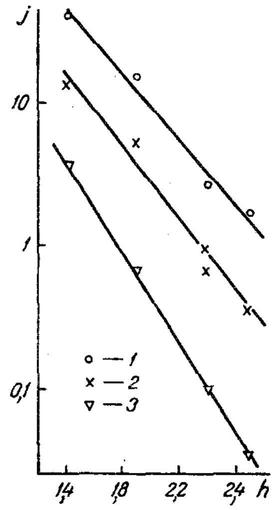

Fig. 3. Descending flux of disperse material (H_0 = 0.46 m): 1) u = 1.90 m/sec; 2) 1.46 m/sec; 3) 1.20 m/sec. j, g/min.

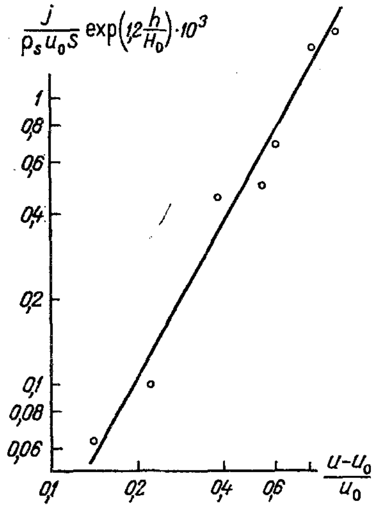

Fig. 4. Generalization of test data with respect to the specific descending flux of decreased material in the space above the bed.

$$\mathrm{Nu}_\infty = 0{,}245\mathrm{Re}^{0,6}. \tag{3}$$

It is seen from the figure that for h = 1.9 m and u = 2.0 m/sec the values of α obtained already practically coincide with those calculated from Eq. (3).

A generalization of the test data on heat exchange in the space above the bed was made on the basis of the function $(\alpha_b - \alpha)/(\alpha - \alpha_\infty) = f(h - H_0/H_0)$, which allows for the limiting cases of $\alpha \to \alpha_\infty$ as $h \to \infty$ and $\alpha \to \alpha_b$ as $h \to H_0$.* The local values of α obtained at different sensor positions in horizontal planes were preliminarily averaged. The results of the generalization are described by the function

$$\frac{\alpha_b - \alpha}{\alpha - \alpha_\infty} = 5{,}5\left(\frac{h - H_0}{H_0}\right)^{1,6}. \tag{4}$$

The root-mean-square deviation of the test data from those calculated from Eq. (4) does not exceed 22% (see Fig. 6). The values of the coefficient of heat exchange in the fluidized bed (α_b) were calculated from the formula [7]

$$\alpha_b = \frac{7{,}2\lambda_f}{d}(1-\varepsilon)^{2/3} + 0{,}044 C_f \rho_f u \frac{(1-\varepsilon)^{2/3}}{\varepsilon}, \tag{5}$$

where $d = 1/\Sigma \eta_i/d_i$ (η_i is the fraction by weight of particles of the fluidized bed with a diameter d_i). The value of α_∞ was determined from Eq. (3).

*Our tests (see Fig. 4 in [7]) showed that for h = H the value of α is less than the average coefficient of heat exchange in the fluidized bed. This is evidently explained by the fact that the upper boundary of the bed undergoes considerable oscillations, and a sensor mounted at the level h = H is periodically uncovered.

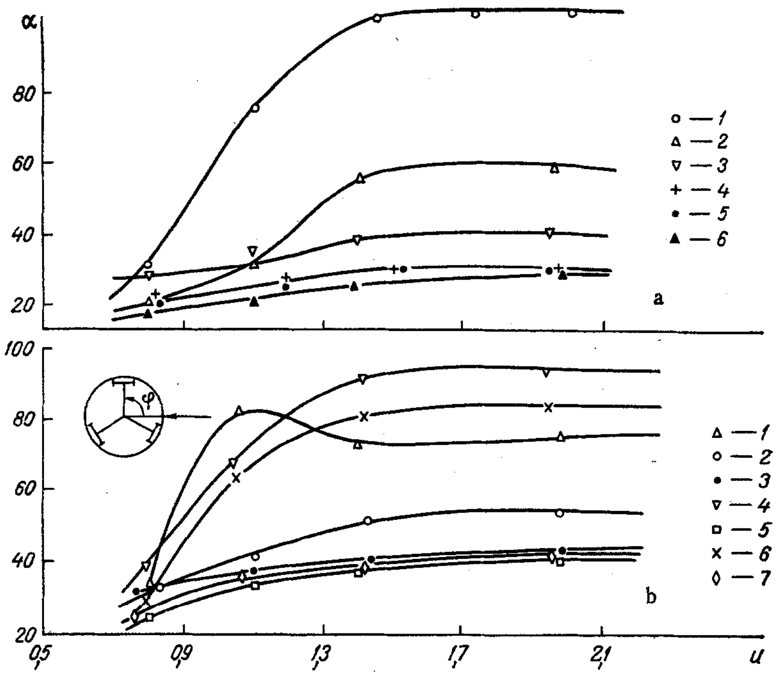

Fig. 5. Coefficient of external heat exchange: a) at the center of the column: 1) h = 0.60 m, H_0 = 0.44 m; 2) 0.83 and 0.54; 3) 1.00 and 0.46; 4) 1.90 and 0.46; 5) 2.40 and 0.46; 6) calculation from (3); b) at the wall of the column: 1) h = 0.66, H_0 = 0.51 m; 2) 0.81 and 0.52; 3) 1.00 and 0.46; 4) 0.62 and 0.47; 5) 1.00 and 0.46; 6) 0.64 and 0.49; 7) 1.0 and 0.46; 1-3) φ = 210°; 4, 5) 90; 6, 7) 330 (φ is the angle in the horizontal plane between the direction of air entry into the chamber below the grid and the radius vector of the center of the sensor). α, $W/(m^2 \cdot °K)$; u, m/sec.

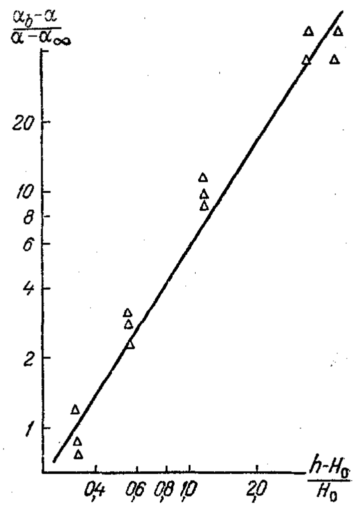

Fig. 6. Generalization of test data on heat exchange in the space above the bed (d = 2.06 mm).

It should be noted that equations similar to (4) were also obtained in [4] to describe heat exchange in the spaces above beds of fine narrow-fraction particles. In that case the authors were unable to generalize data for particles of different diameters by a single function. In our view, a broad generalization of data on external heat exchange in the space above a bed is possible only on the basis of equations of the type (5), which can be constructed using specific physical models of heat exchange, as has been done for the fluidized bed itself (see [7, 9], for example). For the formulation of such models it is necessary to accumulate test data on heat exchange, as well as on the concentrations of particles and their fractional composition in the space above a bed and the dependences of these characteristics on various physical and hydrodynamic factors.

NOTATION

D, outside diameter of tube of the heat-exchange sensor; d, particle diameter; g, free-fall acceleration; h, height above the gas-distribution grid; H, H_0, bed height and initial bed height; H_c, critical height of the separation zone; j, mass of solid particles falling into a "bucket" per unit time; R, residue of particles on a sieve with a mesh d_i; S, horizontal cross-sectional area of a "bucket"; u, u_0, velocities of filtration and of the onset of fluidization; α, α_∞, α_b, coefficients of external heat exchange in the space above the bed, in pure air, and in the fluidized bed, respectively; ε, ε_0, porosities of the bed at filtration velocities u and u_0, respectively; λ_f, coefficient of thermal conductivity of the fluidizing gas; ν_f, kinematic viscosity of the gas; ρ_s, ρ_f, densities of the particles and the gas, respectively; $Ar = gd^3(\rho_s/\rho_f - 1)/\nu_f^2$; $Nu_\infty = \alpha_\infty D/\lambda_f$; $Re = uD/\nu_f$; $Re_c = ud_c/\nu_f$.

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MASS TRANSFER IN A DISPERSE MATERIAL WITH ABSORPTION BY PARTICLES

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The general principles of an average macroscopic description of diffusion mass transfer in disperse media containing surface and bulk sources are elucidated in [1]. In this investigation the mentioned principles are applied to an analysis of diffusion in the gaps between nonconducting particles on whose surfaces absorption and liberation of the diffusing impurity are possible. Such a problem is of direct interest in studying mass transfer processes in suspensions that evaporate and dissolve or grow because of particle condensation and crystallization [2], in granular systems with absorption and heterogeneous chemical reactions [3], in inhomogeneous materials, and particularly, metals with discrete elements of a new phase [4], in certain biological systems [5]. An analogous problem was examined earlier in [6] where certain simplifying phenomenological representations were utilized. In order to obtain the fundamental results in an analytic easily discernible form, we limit ourselves below to an analysis of diffusion in moderately concentrated systems containing spherical particles of identical size. The kinetics of the surface transformations is considered linear while the system itself is spatially homogeneous in macroscopic respects.

We write down the fundamental governing relationships that characterize diffusion in a system with non-conducting particles when the diffusing substance either does not generally penetrate the particle bulk or is not contained within them with a homogeneous concentration. In this case there is a single macroscopic diffusion equation [1]

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