MACROSCOPIC PATTERN OF MIXING OF SOLID PARTICLES IN COLUMNS OF UNITS WITH A FLUIDIZED BED

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The circulation model is used to analyze the effect of the scale factor on the laws governing the mixing of solid particles.

Calculation and modeling of the processes which take place in a fluidized bed under production conditions necessitate detailed study of the laws governing the mixing of solid particles. The practical result of such studies is a model to describe the macroscopic pattern of motion of the particles, along with quantitative data on its parameters.

The minimum requiremet for such a model is an ability to describe the transport of a labeled substance. The results of studies using group and individual labeling of solid particles show that this requirement is satisfied to a greater degree by the circulation model than by the diffusion model normally used. The circulation model reflects the fact that the bed contains ascending and descending flows of solid particles and that particles are exchanged between these zones. In an actual fluidized bed, particles form clusters (packets) which break up, reform, and exchange particles [1]. Packets moving in ascending and descending flows may form at any point inside the layer. Thus, in experiments with tracers, "point" sensors record fluctuations in the concentration of the label (see Fig. 1).

Here, we attempt to experimentally substantiate the feasibility of using the circulation model to describe curves depicting the response to the pulsed introduction of labeled particles into a fluidized bed. The model is based on the concentrations of the label in the ascending and descending flows.

Another goal of the present investigation was to compare the mixing of solid particles corresponding to groups A and B in accordance with Jeldart's classification [2] in different-diameter process unit by means of the circulation model. There is now data on the effect of the properties of solid particles and the diameter of the bed on the effective diffusion coefficient D. As is known, this coefficient is connected with the parameters of the circulation model by the approximate relation $D \cong \omega^2/\beta$. However, from a technical standpoint it is important to know what causes mixing to increase of decrease. For example, a reduction in β is evidence of the formation of packets in the bed; these packets hinder the penetration of reactive gases and may act in which by-products are formed. Thus, we will use the circulation model to interpret the results of study of the mixing of solid particles corresponding to groups A and B in Jeldart's classification.

The equipment and method used to conduct the experiments were described in [3]. We used the method of temperature (thermal) labeling. The height of the fluidized bed was approximately 1.5 and 3 m in columns 0.15 and 0.3 m in diameter, respectively. The fluidized materials were a catalyst in the form of microspheres d_e = 85 μm (group A) and sand d_e = 300 μm (group B).

The information obtained was analyzed on the ASI SIGMA-1 automated scientific research system developed under the direction of I. Ya. Shtral' and M. G. Slin'ko.

Figure 1 shows characteristic response curves obtained in the column 0.30 m in diameter. These curves were analyzed within the framework of the circulation model of mixing:

$$f\frac{\partial\theta_1}{\partial t}+\frac{\partial\theta_1}{\partial\xi}=n(\theta_2-\theta_1),$$

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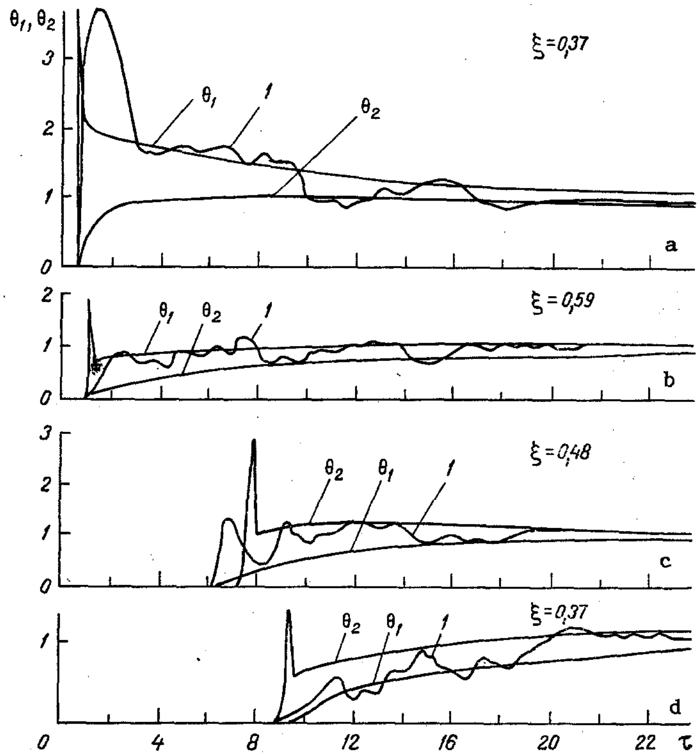

Fig. 1. Comparison of experimental and theoretical response curves: D_C = 0.30 m; H = 2.69 m; u_0 = 0.23 m/sec: a, b) bottom injection of labeled particles; c, d) top injection of same; 1) experimental curves; θ_1 and θ_2) calculation with circulation model. τ, sec.

$$(1-f)\frac{\partial\theta_2}{\partial t}-\frac{\partial\theta_2}{\partial\xi}=n(\theta_1-\theta_2). \tag{1}$$

The circulation velocities u_1 and u_2 were determined from the delay times of the response functions with bottom and top injection of batches of heated particles. The values of f were found from the formula:

$$f=\frac{u_2}{u_1+u_2}, \tag{2}$$

which follows form the equality of the ascending and descending circulatory flows. The exchange coefficient β was calculated from experimentally determined values of the moments of the response curves μ_t and μ_b by means of the expressions [2]:

$$\mu_b=\frac{\beta H^2}{\omega^2}\left(\xi-\frac{\xi^2}{2}-\frac{1}{3}\right)+(1-2f)\frac{H}{\omega}\left(\frac{1}{2}-\xi\right),$$
$$\mu_t=\frac{\beta H^2}{6\omega^2}(f-3\xi^2)+(1-2f)\frac{H}{\omega}\left(\frac{1}{2}-\xi\right). \tag{3}$$

The solution of (1) with boundary conditions corresponding to those created experimentally (see [3]) for temperatures of the ascending flow θ_1 and descending flow θ_2 has the form [4] (for top injection of the heat-labeled particles)

$$\theta_i=1+\exp\left[-n(1-2f)\left(\xi+\xi_0-1+\frac{2t}{1-2f}\right)\right]\times\sum_{k=1}^{\infty}\frac{(-1)^k\sin k\pi\xi_0}{k\pi\xi_0}\left(2\cos k\pi\xi\,\mathrm{ch}\left[n(1-2f)\times\right.\right. \tag{4}$$

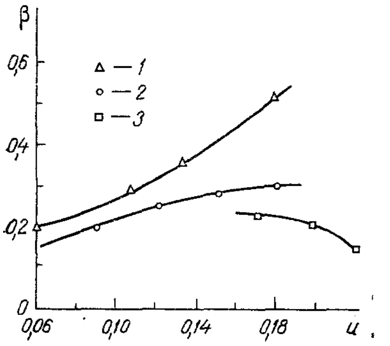

Fig. 2

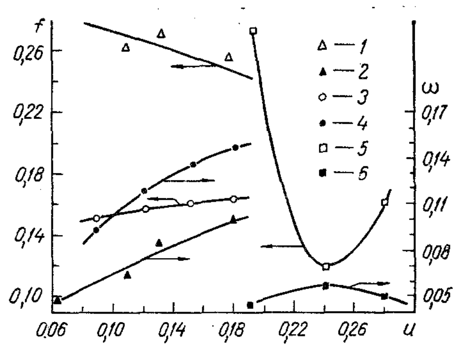

Fig. 3

Fig. 2. Dependence of the exchange coefficient on filtration velocity: 1) D_c = 0.15; 2, 3) 0.30 m (catalyst and sand, respectively). β, 1/sec; u, m/sec.

Fig. 3. Dependence of the parameters f and ω on filtration velocity: 1, 2) D_c = 0.15 m (catalyst); 3, 4) 0.30 m (catalyst); 5, 6) 0.30 m (sand). ω, m/sec.

$$\times\left(\xi+\xi_0-1+\frac{2t}{1-2f}\right)\sqrt{1-\frac{k^2\pi^2}{n^2}}\Bigg]+$$

$$+\frac{2\cos k\pi\xi+\Gamma_i k\pi\sin k\pi\xi}{\sqrt{1-\frac{k^2\pi^2}{n^2}}}\,\mathrm{sh}\left[n(1-2f)\left(\xi+\xi_0-1+\frac{2t}{1-2f}\right)\sqrt{1-\frac{k^2\pi^2}{n^2}}\right]\Bigg), \qquad (4)$$

where $\Gamma_1 = 2/n$; $\Gamma_2 = -2n$.

The solution for bottom injection of the labeled particles is obtained from (4) by making the substitutions $\xi \to 1-\xi$; $f \to 1-f$; $\Gamma_i \to -\Gamma_i$.

Figure 1 shows results of comparison of experimental curves of the response to the pulsed injection of heat-labeled particles and curves calculated with functions (4). It is evident that the temperatures θ_1 and θ_2 agree rather well with the test data. This shows that the circulation model is not only capable of describing averaged values of temperature θ, but it also makes it possible to reliably evaluate the amplitude of temperature pulsations caused by the entry into the chosen region of the bed particles moving in both ascending and descending sections of the circulation loop. Here, as was shown in [3], the mean temperatures calculated from the circulation model agree significantly bettern with the test data than values obtained from the traditional diffusion model of longitudinal mixing.

Figures 2-4 show the dependences of the quantities u_1, u_2, f, ω, and β on filtration velocity. As before, we note that the velocities of particles in the ascending flow u_1 are comparable to bubble velocities only for the catalyst (the material of group A) in the column 0.3 m in diameter. With a diameter of 0.15 m for the bed, the value of u_1 for the catalyst is decreased by a factor of almost two. For sand (group B), particle velocity in the ascending flow is 2-3 times lower than the rate of rise of bubbles with bed diameters of 0.15 and 0.3 m.

The results obtained indicate the possibility of the settling of "trains" of bubbles.

A lower mixing rate was noted for material of group B compared to group A. This difference can be attributed to a substantial reduction in the velocities of the solid particles in the ascending and descending flows. Lower values of the exchange coefficient β were also obtained for the sand. This shows that there is a somewhat greater probability of the formation of concentration and temperature discontinuities when processes are conducted in fluidized beds of materials similar to group B. It should also be noted that the values of exchange coefficient β determined by the moments method and on the condition of the best agreement between the experimental and calculated (from the circulation model) response curves are satisfactorily close to one another. Thus, due to its simplicity, the moments method can be recommended for evaluating the exchange coefficients.

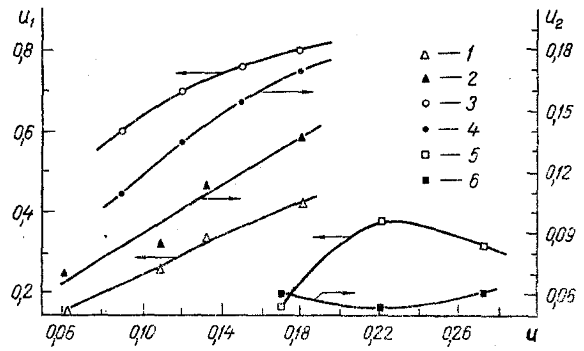

Fig. 4. Dependence of particle circulation velocities on filtration velocity. The notation is the same as in Fig. 3.

In conclusion, we note that the present study is but one of the first attempts to systematically study the parameters of the circulation model (ω, f, and β). To make effective practical use of the model, further studies should be conducted within a broad range of experimental conditions. This will make it possible to obtain generalized relations for calculating these parameters, as is done for the coefficient of longitudinal diffusion D [1, 4]. Allowance should also be made for the asymptotic relationship between the parameters of the diffusion and circulation models $D = \omega^2/\beta$. As is easily shown, this equation follows from the fact that, for steady-state mixing conditions, system (1) becomes the usual diffusion equation with a coefficient equal to ω^2/β.* Use of the above equation would make it possible to in turn use the numerous values obtained for D in generalizing the parameters of the circulation model (and especially when determining their dependence on the scale factor).

NOTATION

D_c, column diameter; D, coefficient of longitudinal diffusion of particles; f, fraction of volume of the emulsion phase occupied by bubble trails; g, acceleration due to gravity; H_0, height of stationary bed; H, height of fluidized bed; $h = V_h/S$; $n = \beta\tau_{ci}$; S, area of horizontal section of bed; $t = \tau/\tau_{cr}$; T, T_0, T_∞, temperature, initial and final temperature of bed; u_0, filtration velocity; u_1, u_2, velocities of bubble trails and downward velocity of particles; V_h, volume fraction of heated particles; x, longitudinal coordinate; β, exchange coefficient; $\theta = (T - T_0)/(T_\infty - T_0)$; $\xi = x/H$; $\xi_0 = h/H$; τ, time; $\tau_{ci} = H/u_1 + H/u_2$, circulation; $\omega = fu_1 = (1 - f)u_2$, circulation velocity of paticles referred to the bed cross section occupied by the emulsion phase. Indices: 1, bubble trails; 2, descending emulsion phase; t, top injection of heat-labeled material; b, bottom injection of same.

*It was shown in [5] that in the general case, the relation between the diffusion coefficient and the parameters of the circulation model has the form $D = \frac{\omega^2}{\beta}\left[1 - \exp\left(\frac{\beta\tau}{(1-f)f}\right)\right]$.

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