CIRCULATION MODEL FOR DESCRIBING MIXING OF SOLID PARTICLES IN A FLUIDIZED BED

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We present experimental response curves for the pulsed introduction of labeled (heated) particles into a fluidized system with a noncirculating solid phase, and compare these curves with those calculated by using the circulation and diffusion models.

In investigating reaction and mass-transfer processes in a fluidized bed it is of fundamental importance to determine the structure of the solid-particle mixing model. In many cases the diffusion and circulation models give identical results in the calculation of steady-state temperature and concentration distributions [1], but give different descriptions of the propagation of perturbations in the bed.

There are technological processes in a fluidized bed whose implementation depends on the mixing mechanism. Thus, for example, it was proposed in [2] to chlorinate powdered aluminum in a fluidized bed of inert particles. The aluminum is introduced into the upper part of the bed, and maintained in a suspended state by a flow of chlorinating gas. The powdered aluminum and chlorine are fed at such rates that the reaction zone is above the gas-distributing mechanism; i.e., the aluminum particles do not reach the lower boundary of the bed. For mixing described by the classical diffusion equation the aluminum particles would always reach the gas-distributing mechanism. A mathematical model of the reactor based on the circulation model of mixing of solid particles can predict such a process. An investigation of a cold analog of the reactor should give information on the structure of the model for describing the mixing of solid particles.

Oigenblik et al. [3] investigated the particle mixing mechanism in various sized devices and compared the moments of the response curves for the pulsed injection of heated particles with the moments calculated theoretically by the diffusion and circulation models. The purpose of the present article is to test the possibility of describing the response curves themselves by the circulation model.

A schematic diagram of the experimental arrangement is shown in Fig. 1. It consists of a plastic column 0.3 m in diameter with fittings uniformly distributed over the height for the insertion of thermocouples with unshielded beads made of Chromel—Copel wires 0.15-0.2 μm in diameter. Heated particles were injected by upper or lower "guns" consisting of electrically heated tubes with an open exit end. An inclined plate was located opposite the exit end of the upper "gun," and a cone opposite the lower "gun" to serve as reflectors. The dispersed material, consisting of microspheric particles of catalyst 85 μm in diameter on the average, was loaded into the column and suspended by air which was first moistened in a bubbling apparatus to lower the static electrification of the particles. A bed 2.69 m deep was maintained for an air speed of 0.23 m/sec.

A pulse of heated particles was injected by a thrust of air from the reservoir and then a rapid cutoff of the supply to the "gun." The instant of introduction of a marker into the column was recorded by a thermocouple near the "gun." Since the experiment lasted 10-100 times as long as the time of injection of a marker into the bed, the pulse was considered instantaneous. The temperature perturbations in the bed were determined by thermocouples at various distances from the place of introduction of the marker, and were recorded on oscillograph film (Figs. 2 and 3).

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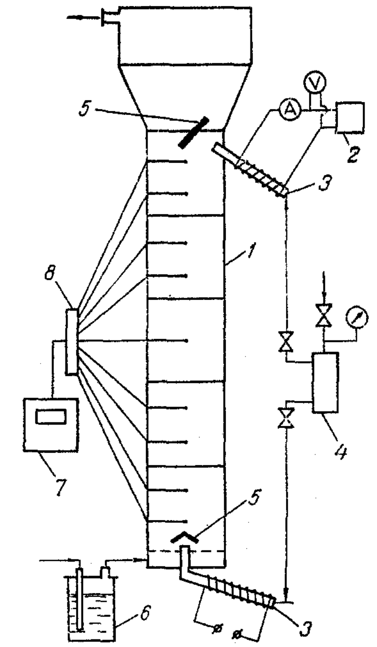

Fig. 1. Schematic diagram of experimental arrangement: 1) column; 2) laboratory autotransformer; 3) heater-"gun"; 4) reservoir; 5) reflector; 6) moistener; 7) oscillograph; 8) thermocouples.

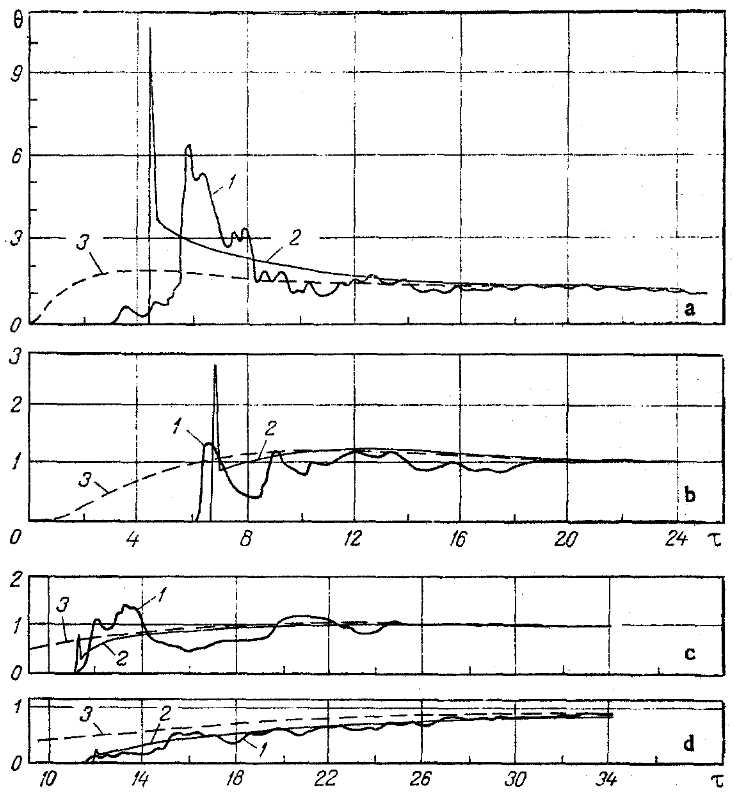

Fig. 2. Comparison of experimental and theoretical response curves. Top introduction of labeled particles: a) $\xi = 0.70$; b) 0.48; c) 0.29; d) 0.10; 1) experimental curve; 2, 3) curves calculated with circulation and diffusion models, respectively. τ is in sec.

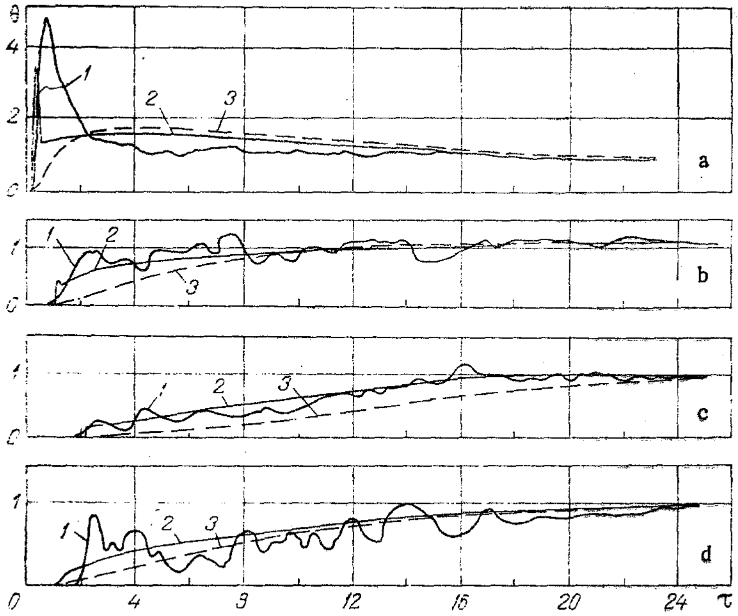

Fig. 3. Comparison of experimental and theoretical response curves. Bottom introduction of labeled particles. a) $\xi = 0.29$; b) 0.59; c) 0.90; d) 0.70; 1-3) see Fig. 2.

The maximum heat losses (Q_L) in the experiment were estimated with the formula [3]

$$Q_L/Q_M < 1.33\tau^*/\tau_L + \tau^*/\tau_s \tag{1}$$

where τ^* is the time of the experiment, $\tau_L = c_s\rho_b H/c_g\rho_g u$, $\tau_s = c_s\rho_b H/\alpha F_{rel}$, and Q_M is the amount of heat introduced into the bed.

The transport of heated particles in the system was modeled within the framework of the circulation model of longitudinal mixing. The equations of this model can be written in the following dimensionless form:

$$f\frac{\partial\theta_1}{\partial t} + \frac{\partial\theta_1}{\partial\xi} = n(\theta_2 - \theta_1),$$
$$(1-f)\frac{\partial\theta_2}{\partial t} - \frac{\partial\theta_2}{\partial\xi} = n(\theta_1 - \theta_2). \tag{2}$$

The following boundary conditions are appropriate to the experiment being performed:

top introduction of heated particles

$$t = 0 \quad \theta_1 = \theta_2 = \begin{cases} 1/\xi_0, & 1-\xi_0 < \xi \leqslant 1, \\ 0, & 0 \leqslant \xi < 1-\xi_0, \end{cases} \tag{3}$$
$$t > 0 \quad \theta_1 = \theta_2, \ \xi = 0;\ 1.$$

bottom introduction of heated particles

$$t = 0 \quad \theta_1 = \theta_2 = \begin{cases} 1/\xi_0, & 0 \leqslant \xi < \xi_0, \\ 0, & \xi_0 < \xi \leqslant 1, \end{cases}$$
$$t > 0 \quad \theta_1 = \theta_2, \ \xi = 0;\ 1. \tag{4}$$

The solution of (2), (3) for the dimensionless temperature $\theta = f\theta_1 + (1-f)\theta_2$ averaged over a horizontal cross section of the bed has the form [4]

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

$$\times \sqrt{1-\frac{k^2\pi^2}{n^2}}\Bigg] + \frac{2\cos k\pi\xi + \frac{4f-2}{n}\, k\pi \sin k\pi\xi}{\sqrt{1-\frac{k^2\pi^2}{n^2}}} \times$$

$$\times\, \mathrm{sh}\left[n(1-2f)\left(\xi+\xi_0-1+\frac{2t}{1-2f}\right)\sqrt{1-\frac{k^2\pi^2}{n^2}}\,\right]\Bigg). \tag{5}$$

The solution of problem (2)-(4) is obtained from (5) by replacing ξ by $1-\xi$, and f by $1-f$.

Figures 2 and 3 compare the response curves obtained for the introduction of a pulse of heated particles with those calculated with functions (5) for top and bottom introduction of heated particles.* The circulation velocities u_1 and u_2 were determined by the delay time of the experimental response functions for the bottom and top introduction of heated particles, respectively. Their average values turned out to be u_1 = 150 cm/sec, and u_2 = 18 cm/sec. The exchange coefficient β, found from the difference between the calculated and experimental response functions by the least-squares method, was 0.3 1/sec.

For comparison, Figs. 2 and 3 also show the form of the response functions according to the classical diffusion model corresponding to the boundary-value problem for top loading:

$$\frac{\partial\theta}{\partial\left(\frac{D\tau}{H^2}\right)} = \frac{\partial^2\theta}{\partial\xi^2}, \tag{6}$$

$$t=0 \quad \theta = \begin{cases} 1/\xi_0, & 1-\xi_0 < \xi \leqslant 1, \\ 0, & 0 \leqslant \xi < 1-\xi_0, \end{cases}$$

$$t>0 \quad \partial\theta/\partial\xi = 0, \quad \xi = 0;\ 1. \tag{7}$$

The initial condition for bottom loading is the same as in (4). The solution of (6), (7) has the form [5]

$$\theta = 1 + 2\sum_{k=1}^{\infty} \frac{\sin k\pi\xi_0}{k\pi\xi_0} \cos k\pi(1-\xi) \exp\left(-k^2\pi^2\frac{D\tau}{H^2}\right). \tag{8}$$

We note here that function (8) goes over into (5) for $\beta = \infty$, $\omega = \infty$, and $D = \omega^2/\beta < \infty$, which reflects the transition in this case of the equation

$$\frac{\partial T}{\partial\tau} + \frac{f(1-f)}{\beta}\frac{\partial^2 T}{\partial\tau^2} + \frac{(1-2f)\,\omega}{\beta}\frac{\partial^2 T}{\partial\tau\partial x} = \frac{\omega^2}{\beta}\frac{\partial^2 T}{\partial x^2}, \tag{9}$$

which is equivalent to system (2), into the classical diffusion equation with the diffusion coefficient $D = \omega^2/\beta$. Therefore, we compared the response curves calculated with a value of 660 cm^2/sec for ω^2/β in (5), and the same value for D in Eq. (8).

Figures 2 and 3 show that the circulation model describes the experimental relations for the unsteady transport of heated particles much better than the classical diffusion theory does. Here it should be noted that the agreement of the experimental and calculated curves is better for small distances between the point of injection of heated particles and the point where the temperature perturbation is recorded (Figs. 2a and 3a) than for large distances (Figs. 2c and 3c). This is apparently the result of a difference between the experimental and theoretical initial conditions. This difference decreases as the pulse propagates over the length of the apparatus.

NOTATION

c_g, c_s, specific heats of gas and solid particles; D, coefficient of longitudinal diffusion of particles; f, fraction of volume of emulsion phase occupied by bubble trails; F_{rel}, outer surface of bed divided by S; H, height of bed; $h = V_H/S$; $n = \beta\tau_c$; S, area of horizontal

*In evaluating the sum of the infinite series in (5), we took account of the first 1000 terms, ensuring an accuracy of 0.01%.

cross section of bed; $t = \tau/\tau_c$; T, T_0, $\overline{T}$, running temperature, initial, and final temperatures of bed, respectively; u, filtration velocity; u_1, u_2, velocities of bubble trails and descending particles; V_H, volume of batch of heated particles injected into bed from "gun"; x, longitudinal coordinate; α, coefficient of heat transfer from bed to environment; β, exchange coefficient; $\theta_i = (T_i - T_0)/(\overline{T} - T_0)$; $\xi = x/H$; $\xi_0 = h/H$; ρ_g, ρ_b, densities of gas and bed; τ, time; $\tau_c = H/u_1 + H/u_2$, circulation time; $\omega = fu_1 = (1 - f)u_2$, circulation velocity of particles over cross section of bed occupied by emulsion phase.

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INFLUENCE OF FLUCTUATIONS OF THE HEAT-TRANSFER COEFFICIENT ON THE TEMPERATURE AND THERMAL STRESSES IN A PLATE QUENCHED IN A VIBRATING FLUIDIZED BED OF A DISPERSE MATERIAL

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The influence of fluctuations of the heat-transfer coefficient on the evolution of the temperature and thermal-stress fields in a plate is analyzed.

The calculations for heat-engineering equipment with a fluidized bed are carried out, as a rule, using the time-average values of the heat-transfer coefficients between the bed and the heating or cooling surface immersed in it. On the other hand, it is well known that the heat-transfer rate between the (vibrating) fluidized bed and the surface is a time-fluctuating quantity and the amplitude of the fluctuations can be substantial (see [1], etc.). The fluctuations of the heat-transfer coefficient induce temperature fluctuations of the body subjected to heat treatment, and they, in turn, can affect the evolution of stresses and strains in the material of the product. In view of the practical difficulties of implementing the experimental investigation of the problem at the present time, we have undertaken a numerical study. We investigated the specific process of quenching a plate of chromium ball-bearing steel ShKh15 with a thickness of 10 mm in a vibrating fluidized bed of corundum particles with a diameter of 0.046 mm. A corresponding study using the time-average values of the heat-transfer coefficient obtained in [2] has been carried out previously [3]. We use the "packet" theory of heat transfer, which has already been shown [2] to be applicable to a vibrating fluidized bed. The computational procedure was similar to [4], in which the "packet" model was used to study the influence of fluctuations on the heat transfer and temperature fields in a body immersed in a fluidized bed. The process is assumed to be quasisteady, i.e., each successive fluctuation does not differ from the preceding one, and the heat transfer is determined by the continuous replacement of packets at the surface.

To calculate the instantaneous values of the heat flux on the surface of the body, we use the equation

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