MECHANISM OF EXTERNAL HEAT EXCHANGE IN A NONUNIFORM FLUIDIZED BED

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UDC 536.242:621.785:66.096.5

The results of an experimental study of the porosity fluctuations in the boundary zone of a nonuniform fluidized bed are presented.

In contrast to [1, 2], in which data on the average structural-hydrodynamic characteristics of a nonuniform fluidized bed near bodies submerged in it are presented, in the present report the authors used a composite method of studying the pulsations in surface temperature and density (porosity) of the bed near the wall. High-speed motion-picture photography of the processes of formation of the boundary zone of a fluidized bed was carried out synchronously with the recording of the pulsation characteristics. A schematic diagram of the installation (in plan) is presented in Fig. 1.

A flat pickup of the direct-current thermoanemometer type [3] was used as the elementary heat-emitting surface. The pickup was fabricated from platinum foil 5 μ thick which, because of the low mechanical strength, was stretched over a mica base. An air gap was left under the pickup. Depending on the size of the fluidized particles three pickups were used having a width of 2.5 mm and a length of 10, 20.5, and 26 mm, which comprised 0.8-0.87 of the thickness of the fluidized bed (of the length of the section of porosity being monitored). The pickups and conductors were mounted flush with the middle part of the textolite plates having a size of 70 × 20 mm and a thickness equal to the thickness of the bed. The plates were fastened vertically between the transparent walls of the apparatus in which the air-fluidized bed was created.

The porosity of the bed adjacent to the pickup was measured on an x-ray structural analysis instrument of the URS-50I-M type. The apparatus was mounted on the goniometer table between the generator unit and the RSD-2 scintillation counter. The open x-ray beam with a height equal to the width of the temperature-sensitive element and a thickness of from one to five particle diameters, produced with a set of slot diaphragms, irradiated the fluidized bed directly along the surface of the pickup. Simultaneous recording of the thermoanemometer readings and the intensity of the transmitted radiation was performed by an N-700 loop oscillograph. In this case the length of the section of local porosity being monitored was chosen from the condition of minimal gas-bubble size, as well as the condition [4]

$$\frac{B}{d_e} = \sqrt[3]{N(1-\varepsilon)}, \tag{1}$$

where B is the linear dimension of the section of porosity being monitored. In this case the static fluctuations in the determination of the local porosity of the boundary layer, which are due to the dispersion of the medium, did not exceed 1%.

In the tests we used particles of chamotte, corundum, glass, and polystyrene with densities of 1050-3912 kg/m³, having monodisperse fractions from 0.12 to 0.85 mm in size, and with fluidization numbers W = 1-5.

We performed static and dynamic calibration of the circuits for measuring the temperature of the pickup sensor [3] and the porosity (by modulation of the x-ray beam with rectangular

S. M. Kirov Ural Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 29, No. 2, pp. 220-224, August, 1975. Original article submitted January 17, 1975.

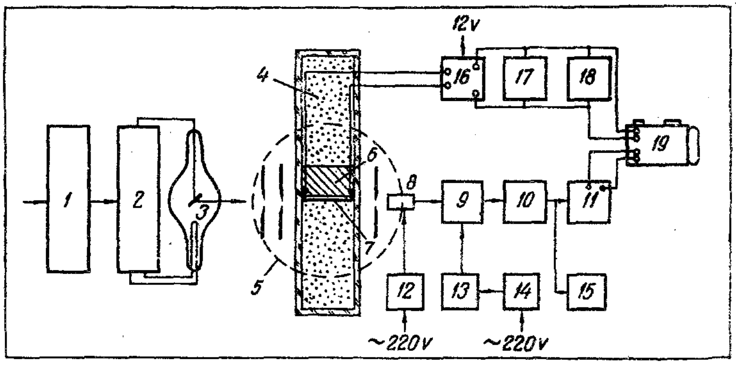

Fig. 1. Block diagram of experimental installation: 1) control panel; 2) generator unit; 3) x-ray tube of type BSVI; 4) apparatus containing fluidized bed; 5) GUR-3 goniometric device; 6) plate; 7) thermoanemometer pickup with conductors; 8) RSD-2 pickup unit; 9) VIII-1 pulse amplifier; 10) ADD-1 automatic discriminator; 11) ISS-1 counting-rate meter; 12) VSV-2 stabilized rectifier; 13) power supply unit; 14) S-0.5 voltage stabilizer; 15) PS-1 scaler; 16) bridge circuit; 17) variable voltage source; 18) millivoltmeter; 19) N-700 loop oscillograph.

pulses of different repetition frequencies). The resolution of the system for determining the porosity was 50,000 counts/sec. The thermal inertia factor calculated for the direct-current thermoanemometer circuit [5] was 0.03 sec.

The characteristics of the formation and dynamics of the boundary zone of the fluidized bed and the effect of its structure on the temperature conditions of the pickup were also studied through synchronous high-speed motion-picture photography by a method developed by the authors [6]. The photography was conducted with an SKS-1M-16 camera with a speed of 200-1200 frames/sec for 7-15 sec in each mode. Synchronization of the photography with the operation of the pickup was accomplished by recording the variable voltage of the MN-7 timing lamp of the camera on the oscillogram.

In accordance with the ergodic hypothesis of fluidized systems of [7], the realizations of the $\varepsilon(\tau)$ and $t(\tau)$ processes with a duration of 15-20 sec were determined in the tests. The statistical analysis of the data obtained, which was first translated into digital code on an F 001 semiautomatic converter, was conducted by the INNA 3 program on a Minsk-22 computer.

The calculated estimates of the probability density $f(\varepsilon)$ of the amplitude distribution of the porosity pulsations, for all the materials used and at a filtration velocity close to the critical value (W = 1.2), can be roughly considered as Rayleigh law distributions

$$f(\varepsilon) = 2k\varepsilon \exp(-k\varepsilon^2), \tag{2}$$

which are characteristic for the case when the oscillating value (the porosity) is distributed in accordance with a normal law at each moment [8]. With an increase in the velocity of the fluidizing agent the distribution curves become deformed (Fig. 2). The probability density of the porosity distribution in a bed of fine corundum particles with d_e = 0.12 mm with W = 2 can be described by a normal law with a positive asymmetry not exceeding 0.5. With an increase in the fluidization number the asymmetry decreases for the given system. For larger particles (d_e > 0.24 mm) (Fig. 2b) the distribution profiles are reorganized into two- and three-peaked profiles with porosities of 0.60-0.65, 0.80-0.85, and 0.95-1.0, corresponding to the maxima of the probability density. Such reorganization is displayed more clearly with an increase in the fluidization number and in the size and density of the fluidized particles.

In Fig. 3 we show the typical appearance of the normalized autocorrelation function for the processes of variation in the porosity of the bed near the boundary (a) and in the pickup temperature (b), from which it is seen that for both processes the curve has a char-

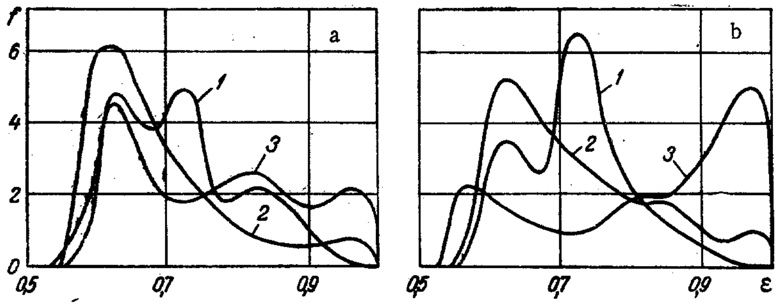

Fig. 2. Probability density of amplitude distribution of porosity pulsations in the boundary zone of a fluidized bed of corundum: a) W = 2; b) 4; 1) d_e = 0.12 mm; 2) 0.24; 3) 0.50 mm.

acteristic corner point at the ordinate, decreases rapidly, and then undergoes oscillations about the null position and can be approximated by an expression of the type [8]

$$R_x(\Delta\tau) = D\exp(-B|\Delta\tau|) + R_y(\Delta\tau), \tag{3}$$

where $R_x(\Delta\tau)$ is the autocorrelation function of the process studied [$\varepsilon(\tau)$ or $t(\tau)$]; $R_y(\Delta\tau)$ is the autocorrelation function of the periodic component of the process.

The correlation time for the $\varepsilon(\tau)$ and $t(\tau)$ processes does not exceed 0.3 sec for all the systems studied, which agrees with the data [9] for the temperature of a similar pickup in a volumetric model. The periodic component of both processes, which has the same frequency as its autocorrelation function $R_y(\Delta\tau)$, is the same for the given system and comprises 3-6 sec^{-1} depending on the fluidization number.

In comparing the $\varepsilon(\tau)$ and $t(\tau)$ oscillograms and estimating the effect of porosity variation on the fluctuation in the pickup temperature and the intensity of heat exchange between its surface and the fluidized bed it is necessary to take into account the phase (time) lag of the $t(\tau)$ curve, which is due to the thermal inertia of the pickup.

The value of the phase shift φ was determined by two methods: from the shift in the characteristic points on the synchronously recorded oscillograms of $\varepsilon(\tau)$ and $t(\tau)$ and by means of calculation [10]. For all the fluidized beds studied the value of the phase shift found by the two methods varies insignificantly and comprises 0.50-0.85 rad.

Using a Minsk-22 computer we calculated the mutual correlation coefficient $\rho_{\varepsilon,t}$ for the $\varepsilon(\tau)$ and $t(\tau)$ processes from the equation [8]

$$\rho_{\varepsilon,t}(\Delta\tau) = \frac{R_{\varepsilon,t}(\Delta\tau)}{\sqrt{R_\varepsilon(0)\,R_t(0)}}. \tag{4}$$

The calculation showed that with the choice of a discreteness interval close to the average value of the phase shift between the experimental $\varepsilon(\tau)$ and $t(\tau)$ curves the value of $\rho_{\varepsilon,t}(\Delta\tau)$ for the different fluidized beds (W = 2-5) lies in the range of 0.72-0.91. Since the correlation coefficient, which carries information on the phase shift between the studied processes, is close to unity, one can conclude that $\varepsilon(\tau)$ and $t(\tau)$ increase or decrease simultaneously with the accuracy of the random errors; i.e., a rather strong stochastic connection, approaching a functional connection, exists between them.

A frame-by-frame analysis of the motion pictures showed that a gas bubble which has formed often comes in contact with the submerged surface not at its core, but through a layer of particles flowing over its side (lateral train of Fig. 4), while the upper part of the bubble is filled with particles spilling from the dome.

The statistical analysis of the $\varepsilon(\tau)$ and $t(\tau)$ fluctuation processes with allowance for the thermal inertia of the pickup along with the data of the synchronous high-speed motion-picture photography showed that the temperature of the sensor increases upon contact with a gas bubble and its lateral train and decreases upon contact with the base of the bubble, which represents a local fluidization source, and with the following hydrodynamic wake. The authors of [11] observed a qualitatively similar picture.

At the same time it turned out that the temperature pulsation of the pickup and its rate of variation $dt(\tau)/d\tau$, calculated from the oscillograms by the method of graphic

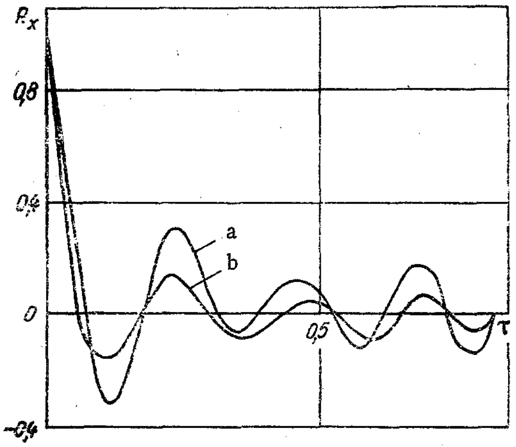

Fig. 3

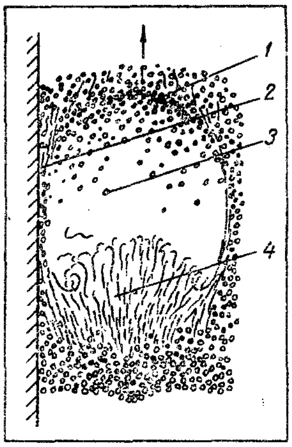

Fig. 4

Fig. 3. Autocorrelation functions of porosity pulsation of the bed near the boundary (a) and of the pickup temperature (b). (Corundum, d_e = 0.24 mm, W = 2). τ, sec.

Fig. 4. Diagram of the rise of a gas bubble and its wake at a vertical surface submerged in the bed: 1) compacted dome; 2) lateral train; 3) core of bubble; 4) hydrodynamic wake of bubble.

differentiation, are an order of magnitude lower than those in [3, 9]. The pulsation in the heat flux, found from the equation [5]

$$q(\tau) = \frac{I^2 R}{F} - (c\rho\delta)_{ef} \frac{dt(\tau)}{d\tau}, \tag{5}$$

corresponding to this did not exceed 5-10% in our experiments. It was also established that at the start of the period of cooling of the pickup the heat-exchange coefficient does not decrease [3, 9] but increases, which is explained by the continuous decrease in the porosity of the fluidized system near the surface of the pickup during this period.

NOTATION

d_e, equivalent diameter of particles, mm; τ, time, sec; ε(τ), instantaneous porosity of bed near the boundary; t(τ), instantaneous temperature of pickup; W, fluidization number; D, dispersion; I^2R/F, thermal power released in pickup per unit surface, W/m^2; $(c\rho\delta)_{ef}$, effective heat capacity of pickup, $J/m^2 \cdot deg$.

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