sionless and dimensional velocity; x, x', y, y', dimensionless and dimensional longitudinal and transverse coordinates; α, angle of inclination of the flat substrate to the vertical; γ, increment of oscillation build-up; ε, "long-waviness" parameter; η, dimensionless film thickness; λ, linear longitudinal scale; ν, kinematic viscosity; ρ, density of the liquid; σ, surface tension; φ, dimensionless amplitude of the wave; Ω, frequency of the wave; ω, complex frequency of the wave; Fi, film number; Re, We, Reynolds and Weber numbers; *, complex conjugation.

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PRESSURE PULSATION MECHANISM IN A NONUNIFORM FLUIDIZED BED

A. P. Baskakov, V. G. Tuponogov, and N. F. Filippovskii

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A model is proposed for pressure oscillations in a fluidized bed. A formula is obtained for the oscillation frequency and calculated values are compared with experimental data.

Three types of pressure pulsations are evidently possible in a nonuniform fluidized bed, which is an oscillatory system. The first type is connected is the washing of the pressure measurement device by a bubble in the bed [1, 2]. The second type is connected with the free oscillations in the system comprised of the bed and the gas inlet. These oscillations determine the state of the bed when the resistance of the gas distributor is low and the pregrate volume is high [3, 4]. The third type of pulsation, which predominates in ordinary nonuniform beds, is connected with the natural frequency of the gravitational oscillations of the bed. Todes [5] proposed a formula to evaluate the frequency of these oscillations $\nu = g^{0.5}/(2\pi H^{0.5})$. It correctly reflects the dependence of ν on H, but the values of the pressure pulsation frequency it gives are only half as great as the experimental values. For near-uniform fluidization conditions, i.e., for shallow beds or low fluidization velocities, the following relation was obtained [6]:

$$\nu = \sqrt{g(2-\varepsilon)}/(2\pi\sqrt{H\varepsilon}). \tag{1}$$

This formula gives the best agreement with the experimental data at ε = 0.4-0.5. However, the assumption of a synchronous change in porosity over the entire height of the bed which was made in deriving the formula is inconsistent with physical representations of particle fluidization, and the authors themselves note that the change in porosity is actually propagated in the form of a wave from the grate to the top boundary of the bed. The present work studies pressure pulsations in the volume of a large apparatus in the regime of intensive bubble fluidization.

Observations show that at the moment a gas bubble escapes, the column of particles underneath the bubble rises. At the same time, the particles in the adjacent regions descend and circulation loops are formed (Fig. 1). To calculate the natural frequency of the bed oscillation, we will simplify the actual situation and represent it in the form of oscillations of an ideal liquid in a U-shaped tube (Fig. 1). The equation describing the oscilla-

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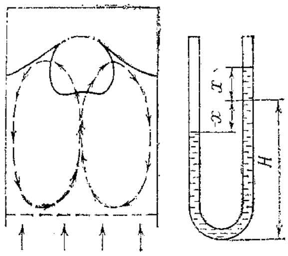

Fig. 1

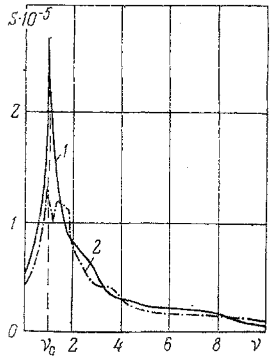

Fig. 2

Fig. 1. Diagram of circulation loops in the bed and the hydraulic pendulum.

Fig. 2. Spectral densities of the pressure pulsations in the bed: 1) h = 0 m; 2) 0.74; ν_0 = 1.04 sec^{-1}; H = 0.8 m; W = 2.6. S · 10^{-5} Pa^2 · sec.

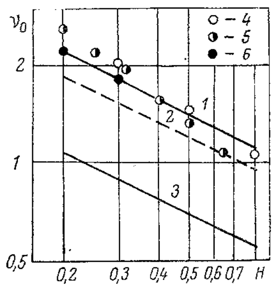

Fig. 3

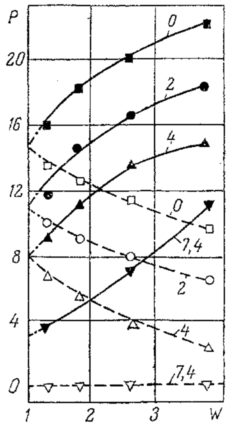

Fig. 4

Fig. 3. Dependence of the natural frequency of pressure pulsations in the bed on the bulk density of the bed: 1) Eq. (4); 2) Eq. (1), ε = 0.5; 3) the formula in [5]; 4) our data; 5) data in [7], glass beads, d = 0.55 mm; 6) data in [6], quartz sand, d = 0.6–0.75 mm. H, m; ν_0, sec^{-1}.

Fig. 4. Dependence of the maximum and minimum pressures in the bed on the fluidization velocity: The numbers next to the curves denote the distance from the gas-distributing grate to the measurement point in decimeters; the dark points denote the maximum values; the clear points denote the minimum values; H = 0.8 m. P, kPa.

tions of this hydraulic pendulum relative to the equilibrium position, in which the initial height of the columns of liquid in both branches is equal to H, has the form

$$\frac{d^2x}{d\tau^2} + \frac{g}{H}\,x = 0 \tag{2}$$

with $x = A\cos[(g/H)^{1/2}\tau]$, where A is the amplitude. Using this equation and its solution gives us the following expression for the pressure in the bottom section

$$P = \rho g(H + x) + \rho(H + x)\frac{d^2x}{d\tau^2} = \rho gH + \rho x\frac{d^2x}{d\tau^2} = \rho gH - \frac{\rho gA^2}{2H}\left(\cos 2\sqrt{g/H}\,\tau + 1\right), \tag{3}$$

and, thus, the pressure pulsation frequency is determined by the formula

$$\nu = \frac{1}{\pi} \sqrt{g/H}\,. \tag{4}$$

In reality, the area of the region of bubble ascent is usually smaller than the surrounding region of downward movement of the material, i.e., in the idealized scheme the tube sections are not of the same size. However, this fact does not affect the frequency of the oscillations.

Equation (4) gives the same result as (1) with $\varepsilon = 0.4$. That is to say, with this value of porosity, good agreement was noted [6] between the experimental results and Eq. (1).

Experimental measurements of characteristics of the pressure pulsations in the bed were conducted on an enlarged unit having a 1.2×0.6 m grate with 18 gas-distributing caps and a cross section of 2.4%. The unit was equipped with apparatus for automatic sampling and analysis of the measurements. Instantaneous pressure values were fed directly into a computer. The transducers, connected to a multichannel data-measurement system and installed at different points in the bed, were interrogated in a prescribed sequence. The maximum interrogation frequency was 135 Hz. The relative error of the pressure measurements was no greater than 1%. We fluidized corundum with a mean particle diameter of 0.4 mm and a bulk density $\rho = 1830$ kg/m^3. The experiments were conducted at bed heights of 0.3-0.8 m in the range of fluidization numbers from 1.3 to 3.8.

The measurements of pressure pulsations at different points of the bed showed that, throughout the range of fluidization velocities, the fundamental frequency is constant for a given bed height. The bubbles which appear with an increase in fluidization velocity expand the pressure oscillation spectrum in the bed, but the maximum of the spectrum, as in the case of fluidization which is close to uniform, is the natural frequency of the bed. This is because the bed itself acts as a resonator adjusted to this frequency (Fig. 2). As the sampling device approaches the grate, the pressure pulsations connected with its washing by the bubbles, which are smaller in the bottom part of the bed, become less noticeable on the background of powerful resonance pulsations. Thus, the maximum of the spectrum is distinct in the bottom part of the bed and less distinct near its surface. Figure 3 compares the experimental values of the natural frequencies of the bed obtained by different authors with the values calculated with Eq. (4).

The amplitude of the pressure pulsations in the bed is determined by the peak-to-peak amplitude of the oscillations of its surface, which in turn depends on the maximum size of the bubbles leaving the bed. Figure 4 shows the maximum positive and negative deviations of the pressure from its mean, taken from histograms of pressure distribution. The amplitudes increase with an increase in the fluidization number but undergo almost no change over the height of the bed until the pressure transducer turns out to be higher than the lowest level of the bed during the oscillation process. In the latter case, the transducer turns out to be in the cavity of a bubble at the moment of its destruction, and the pressure (i.e., the pressure of the gas above the bed) recorded at this moment is zero.

NOTATION

A, amplitude of the oscillations, m; d, particle diameter, mm; g, acceleration due to gravity, m/sec^2; H, bulk bed height, m; h, distance of transducer from grate, m; P, pressure in bed, Pa; S, spectral density of the pressure pulsations, Pa$^2 \cdot$ sec; W, number of fluidizations; x, running height coordinate, m; ε, bed porosity; ν, ν_0, frequency and natural frequency of pressure oscillations in the bed, sec^{-1}; ρ, bed density, kg/m^3; τ, time, sec.

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STUDY OF HEAT EXCHANGE BETWEEN A MODEL PARTICLE AND A FLUIDIZED BED

G. I. Pal'chenok and A. I. Tamarin

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An experimental study is made of heat exchange between an unsecured model particle and a fluidized bed. The test data is generalized with a dimensionless relation.

Work is now being done here and abroad on the development of new burners for low-temperature combustion of solid fuel in a fluidized bed (FB). The new type of burner is capable of operating efficiently on low-grade, coarse-crushed coals and makes it possible to reduce harmful atmospheric emissions [1]. The fuel is fed into an FB of coarse, incombustible particles and comprises 1-3% of the bed weight. Heat transfer from the burning particles to the FB to a large extent determines its temperature and, thus, the kinetics of the reaction occurring on its surface, as well as the condition of the mineral part of the fuel. The last-mentioned factor is particularly important, since fusion of the ash may lead to sintering of the particles and disruption of the operation of the burner.

The literature contains extensive information on the heat exchange of an FB with stationary surfaces submerged within it [2, 3]. However, in the system being discussed here the particle is not stationary and participates in the complex circulating movement of the material in the FB. Meanwhile, its dimensions and density are different from the dimensions and density of the inert particles. The data in [4], obtained by measurement of the temperature and time of combustion of a single coke particle in a fluidized bed in a 40-mm-diameter column, showed that the dimensions of the fuel particle affects the rate of heat transfer.

We had the goal of taking a detailed look at the heat exchange between a movable model particle and an FB under "cold" conditions and determining how it is affected by the physical parameters of the particle itself and the material of the bed, as well as the hydrodynamics and scale of the system.

The tests were conducted in apparatuses of circular (150 mm diameter) and rectangular (400 × 250 mm) cross section. The apparatuses had transparent windows permitting observation of the bed. In both apparatuses, we used gas-distributing grates in the form of perforated metal plates with a layer of dense cloth pressed between them. To ensure uniform gas distribution, the chambers under the grates were filled with spherical packing. The bed was fluidized with room-temperature air. The rate of flow of the air was measured with an accuracy no worse than ±3% from the pressure drop after a standard diaphragm. Table 1 shows characteristics of the dispersed materials used. The initial height of the bed in the tests was not changed and was 150 and 250 mm, respectively, for the small and large apparatuses.

The heat-transfer coefficient was determined by the method of regular thermal regime [5]. The combination aluminum transducer and model particle with a caulked-in thermocouple was heated in molten tin to about 250°C and thrown into the FB. Since the value of the Bi criterion did not exceed 0.01 in the tests and the nonuniform temperature over the cross section of the transducer could be ignored [5], the average heat-transfer coefficient over the surface was equal to $\alpha = mcG/F$.

The temperature of the bed was measured with a thermocouple with an open junction. The temperature difference between the transducer and the FB was recorded by a potentiometer to within 0.5°K, which ensured

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 45, No. 3, pp. 427-433, September, 1983. Original article submitted June 10, 1982.