RELAXATION AUTOOSCILLATIONS OF A GRANULAR BED

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Instability and autooscillations of a fluidized bed having an empty space under the gas distributor plate are investigated experimentally. The results are used to test a theoretical model proposed earlier.

Many devices with a fluidized bed have an empty space under the supporting plate which is accessible to the fluidizing gas. This space is frequently comparable with or even larger than the volume of the bed itself. In particular, the cavities which are always present in gas supply systems to smooth the velocity, etc., contribute to this space. As shown in [1], extra compressed gas can accumulate in such cavities, and the subsequent rapid escape of the excess gas through the expanding bed as bubbles can, under certain conditions, lead to a specific instability of the fluidization process which can significantly affect the operating characteristics of the devices.

The instability mentioned can lead either to the establishment of a periodic fluidization regime when the macroscopic parameters of the bed, which is constantly in a truly fluidizing state, undergo regular oscillations about their average values or, more frequently, to a regime of relaxation autooscillations. In the latter case the granular bed remains in a stationary state during a certain fraction of the autooscillation cycle; i.e., it lies at rest on the plate. Under these conditions the lower surface of the bed does not lose contact with the gas distributor plate, and the observed expansion of the bed results from the increase of the relative volume of bubbles in it. A piston-like motion of the granular bed without the formation of bubbles within it is possible also provided the actual fluidization curve has a maximum [2]. One can expect that in principle either of these mechanisms can operate depending on the type of apparatus and the characteristics of the process. We note that autooscillations resulting from a cavity under the plate have often been observed experimentally [3, 4].

From a purely practical point of view it is very important to estimate beforehand the conditions under which the appearance of an instability should be expected and also the parameters which result from the unsteady regime. Therefore, the experimental test of models describing autooscillations of various types becomes particularly important. We report some experimental results and compare them with certain model concepts.

The experimental arrangement permitted varying the volume of the space under the gas distributor plate, the plate itself, and the volume of the column containing the granular bed. Rectangular plastic columns with cross sections 100 × 100, 150 × 150, and 200 × 200 mm were used; the perforated plastic gas distributor plates of various cross sections had holes 2 mm in diameter. The volume of the cavity was varied by connecting extra receptacles with a capacity up to 300 liters and by using partially filled water tanks.

The fluidizing agent was air supplied by a rotary blower through a 50-mm-diameter pipeline. The air supply rate to the apparatus was controlled by bleeding part of the flow into the atmosphere through a valve; the flow rate of the air was measured with a special measuring washer and a set of diaphragms. The granular material consisted of sieve fractions of washed quartz sand having equivalent particle diameters of 0.25 or 0.75 mm. The bulk density of the granular material was 1510 kg/m^3, and the minimum fluidization velocity was 5 or 25 cm/sec, respectively. Pulsations of the air velocity were measured with a hot-wire anemometer and pressure pulsations, with low-inertia induction-type transducers [5].

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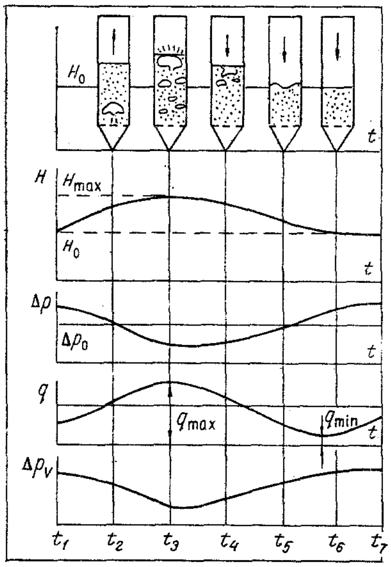

Fig. 1

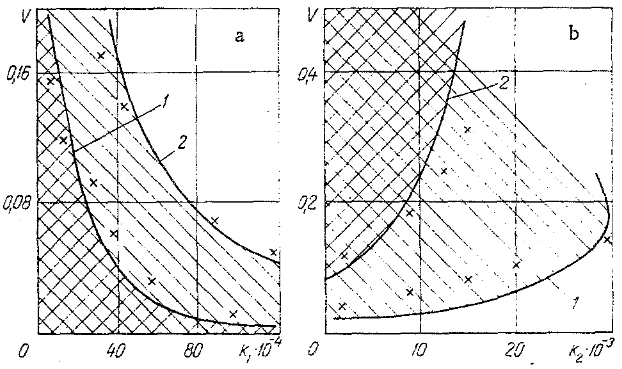

Fig. 2

Fig. 1. Variation of parameters of granular fluidized bed during an autooscillation cycle.

Fig. 2. Effect of coefficients k_1 and k_2 on the critical values of the volume V of the cavity corresponding to the loss of stability. The particle diameters are 0.25 mm (1) and 0.75 mm (2); H_0 = 0.15 m, S = 0.01 m^2; a) k_2 = 7722 $(m \cdot sec)^{-1}$; b) k_1 = 386100 $(m \cdot sec)^{-1}$. The points are experimental and the curves from theory. V, m^3.

The amplitude and frequency of oscillations of the bed level were found from frames of high-speed photographs. The inner structure of the fluidized bed was investigated at various stages of the autooscillation cycle by using x-ray apparatus with electrooptical transformation of x-ray to optical images and then to moving pictures which were synchronized with the oscillographic recording of the oscillations of air pressure and velocity.

Under our experimental conditions autooscillations were produced by the mechanism corresponding to the model in [1]. The characteristic variation of the state of the bed and its observable parameters during an autooscillation cycle are shown in Fig. 1. The time interval from t_6 to t_7 corresponds to the static part of the cycle when the bed is at rest; an estimate of the length T_1 of this interval can be found in [2]. The interval from t_1 to t_6 is the dynamic part of the cycle; its duration T_2 can be found by solving equations in [1]. Both the relative pressure Δp_V in the cavity under the plate and the pressure drop in the bed Δp are maximum at the time t_1. The maximum flow rate of air through the bed occurs close to the time of the largest expansion of the bed and the minimum just before the bed comes to rest. The observed phenomenological picture, described also in [4], agrees qualitatively with the physical model of the autooscillation process following from [1].

The procedure for determining the boundaries of the stable region in the space of various parameters is described in [4]; it is based on fixing the instant when autooscillations cease, i.e., the transition from fluidization to the stationary state during a smooth variation of the volume V of the cavity by filling the tanks with water while keeping the other parameters fixed. As an example, Fig. 2 shows the experimental points corresponding to the curve of neutral stability for various values of the coefficients of hydraulic resistance of the air supply system (k_1) and the gas distributor plate (k_2) which are of the greatest practical interest. Figure 3 shows the dependence of the period of autooscillations on the initial height of the bed and on the volume of the cavity for given resistance coefficients.

Theoretically, the variation of the observable parameters of the process during the dynamic stage of the autooscillation cycle can be described on the basis of the solution of equations derived in [1] and in the static stage, by starting from the results in [2]. We note that to simplify the models in [1, 2] it was assumed that the characteristic of the gas blower does not depend on its output and that the hydraulic resistance of both the gas supply system and the gas distributor vary linearly with the flow rate. In actual equipment these resistances are generally nonlinear, and the pressure produced by the gas blower depends critically on the volume of gas delivered. On the basis of the models in [1, 2] the first difficulty is easily circumvented in practical

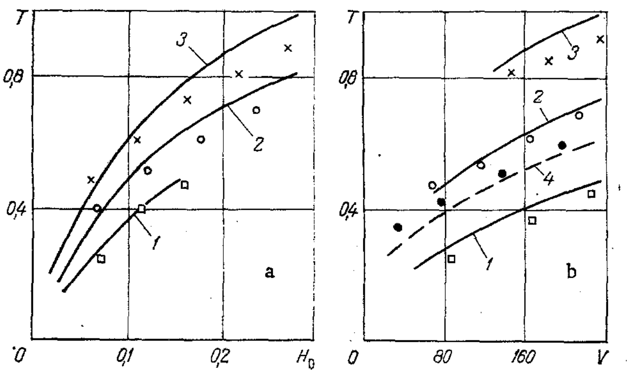

Fig. 3

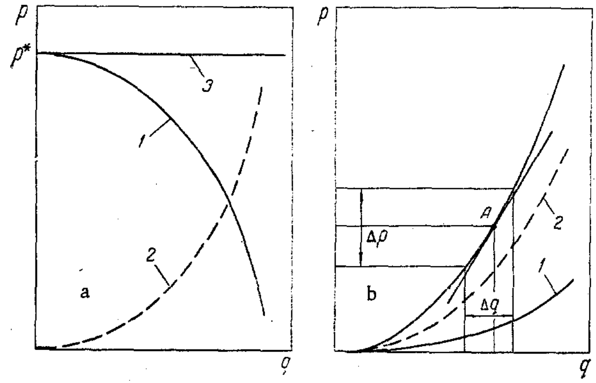

Fig. 4

Fig. 3. Period of autooscillations as a function of initial height of bed H_0 and volume of cavity V; k_1 = 965,000, k_2 = 3861 $(m \cdot sec)^{-1}$, S = 0.01 m^2; a) particle diameter 0.25 mm; 1) V = 0.08; 2) 0.14; 3) 0.24 m^3; b) 1-3) particle diameter 0.25; 4) 0.75 mm; 1) H_0 = 0.075; 2) 0.15; 3) 0.28; 4) 0.15 m. Points are experimental and curves from theory. T, sec; H_0, m; V, $m^3 \cdot 10^{-3}$.

Fig. 4. Determination of characteristic of a fictitious gas blower (a) and corresponding k_1 (b). $k_1^{(A)} = \Delta p/\Delta q$.

calculations by using differential resistance coefficients determining the local slope of the corresponding characteristics; the second difficulty can be eliminated by a formal procedure described below.

Suppose the characteristic of the gas blower is described by curve 1 of Fig. 4a. By formally inserting into the gas supply line an additional resistance with a characteristic represented by the mirror image of the characteristic of the gas blower (curve 2 of Fig. 4a) we obtain the characteristic of a certain fictitious gas blower (curve 3) which does not depend on output. Then combining the actual resistance curve of the gas supply line 1 with the curve corresponding to the fictitious additional resistance (2 in Fig. 4b) we obtain the effective characteristic of the resistance of the gas supply line (curve 3) which must be used in all calculations together with the characteristic of the fictitious gas blower discussed above.

Figure 2 shows estimates of the boundaries of the stable region (curves of neutral stability) according to the model in [1]. The period of the autooscillations, also estimated from solutions of equations in [1], is shown by the curves of Fig. 3. It is clear that the theoretical model leads to results in satisfactory agreement with the experimental data. This agreement can be improved if first the original nonlinear equation [1] and not its linearized variant is used to describe the dynamic stage of the autooscillation cycle, as actually was done in the calculation of the theoretical curves in Figs. 2 and 3, and, secondly, by giving up the condition for a strict isothermal process imposed in [1, 2] to simplify the calculations. These refinements present no difficulty in principle, and therefore will not be discussed further.

In addition, we investigated the dependence of the autooscillation characteristics on certain other quantities (e.g., the cross-sectional area of the column with the granular bed). Good agreement with theory was observed here also. On the whole, it can be concluded that the autooscillation regime actually observed can be adequately described by the model proposed in [1], even in its simplest linearized version, which is clearly sufficient for most applications. In particular, all the basic qualitative conclusions on the character of the dependence of the autooscillation parameters on the geometric characteristics of the system and the parameters of the process following from the model mentioned turned out to be valid. Also the quantitative agreement between theory and experiment is not bad.

NOTATION

H_0, height of bed in the state of minimum fluidization; S, cross-sectional area of bed; k_1, k_2, resistance coefficients of gas supply system and gas distributor plate; V, volume of cavity under gas distributor plate; Δp, pressure drop in bed; Δp_V, relative pressure in cavity under plate; p*, relative pressure at gas blower outlet; t, time; T_1, T_2, lengths of static and dynamic stages of autooscillation cycle; q, total mass flow rate of gas entering bed.

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ACCURACY OF DETERMINATION OF THE DENSITY OF A GAS BY THE MULTIBEAM-INTERFEROMETRY METHOD

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We estimate the accuracy of the determination of the density of a gas in rarefied streams by using the photometric method of multibeam interferometry. We give the numerical values of the relative error in the measurements for various experimental conditions.

Measurement of the density of rarefied gas streams may be carried out by the method of multibeam interferometry [1], based on the multiple passage of a beam of light through the gas stream investigated. The special feature of the method is that the measurements are more sensitive than in the case of two-beam interferometry, so that quantitative investigations can be made in streams at a static pressure of as little as $1\text{-}5 \cdot 10^{-2}$ torr [2, 3], and, in particular, it is possible to determine the shape of the density jump, the start and thickness of the shock wave, etc.

In what follows, we shall estimate the accuracy of density measurements beyond the jump by the multibeam-interferometry method, with the interferometer adjusted to a field of equal illumination (a "band of infinite width") and with photometric decoding of the interferograms [2, 3].

The density ρ_2 beyond the jump is defined in general form as

$$\rho_2 = \rho_1 + \Delta\rho, \tag{1}$$

where ρ_1 is the density of the incoming stream; $\Delta\rho$ is the increment of density, which has the form [3]

$$\Delta\rho = \frac{2.3\,\Delta D_2 \varepsilon}{\gamma} \cdot \frac{(1 + 2.3\,\Delta D_1/\gamma)^2}{(2.3\,\Delta D_1/\gamma)^{1/2}}, \tag{2}$$

where ε is a coefficient that is constant for a given measurement and depends on the wavelength of the monochromatic light, the reflection coefficient of the mirrors, and the distance between them [3]; ΔD_1 and ΔD_2 are the values of the optical densities of blackening of the photographic material at the measured points of the field in the incoming-stream region and beyond the jump, respectively.

The relative error in the density measurements can be represented as

$$\frac{\Delta\rho_2}{\rho_2} = \frac{\Delta(\rho_1 + \Delta\rho)}{\rho_1 + \Delta\rho} = \frac{\Delta\rho_1}{\rho_1} \cdot \frac{1}{1 + \dfrac{\Delta\rho}{\rho_1}} + \frac{\Delta(\Delta\rho)}{\Delta\rho} \cdot \frac{1}{1 + \dfrac{\rho_1}{\Delta\rho}}, \tag{3}$$

and, consequently,

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