LITERATURE CITED

1. Z. R. Gorbis and V. A. Kalender'yan, Heat Exchangers with Dispersed Flowthrough Heat-Transfer Agents [in Russian], Énergiya, Moscow (1975).
2. V. G. Kashirskii and Yu. Ya. Pechenegov, Inzh.-Fiz. Zh., 25, No. 1 (1973).
3. V. M. Legkii and A. S. Makarov, Inzh.-Fiz. Zh., 20, No. 2 (1971).
4. B. S. Petukhov, Heat Exchange and Resistance in Laminar Fluid Flow in Pipes [in Russian], Énergiya, Moscow (1967).
5. Yu. Ya. Pechenegov and V. G. Kashirskii, Izv. Vyssh. Uchebn. Zaved., Énerg., No. 9 (1974).

STABILITY OF OPERATION OF APPARATUS CONTAINING HEATED FLUIDIZED BEDS

V. A. Borodulya, Yu. A. Buevich, and V. V. Zav'yalov

UDC 621.783.2:66.096.5

The influence of temperature on the conditions of disturbance of stability and the establishment of a self-oscillatory mode of fluidization is investigated.

It was shown earlier that the fluidization process becomes unstable under certain conditions in apparatus containing fluidized beds which are characterized by a "free" subgrid chamber of relatively large volume and a gas-distribution grid of low hydraulic resistance [1]. A disturbance of stability leads to "driving" of the system with the ultimate establishment of a self-oscillatory mode of fluidization. Such a mode was studied theoretically and experimentally in detail in [2, 3] under ordinary conditions, i.e., with fluidization by a cold gas.

Sometimes, especially in apparatus of large size containing large amounts of granular material, self-oscillations are an undesirable phenomenon, since they lead to the appearance of cyclic impact loads on the gas-distribution grid and other elements of the structure of the apparatus with their possible destruction. At the same time, self-oscillations promote better mixing of the granular material and intensification of various bulk processes carried out in a granular bed, and in a number of cases they can be considered as a natural and easily attainable means of improving the working characteristics of the apparatus. The investigation of the stability of the fluidization process and the parameters of self-oscillation cycles under conditions reflecting the operation of real apparatus therefore turns out to be very important in a practical respect.

First of all, the temperature dependence of the region of stability in the space of the parameters of the process is of undoubted interest. In fact, real apparatus usually operate at elevated temperatures, and some of the important parameters vary quite strongly with a change in temperature. The results of the experimental research in [2, 3], carried out on "cold" laboratory installations, obviously cannot be employed directly in an analysis of "hot" industrial apparatus; but qualitative conclusions about the influence of temperature on the stability of the fluidization process can be drawn on the basis of the general theory in [1], which remains valid as before.

For this it is sufficient to use the equation determining the boundary of the region of stability [1],

$$v_{1,2}=\frac{1}{2n}\left[\frac{1}{Nn}-1-n\right]\left\{1\pm\left[1-\frac{4}{N}\,\frac{1+n}{[(Nn)^{-1}-1-n]^2}\right]^{1/2}\right\}. \tag{1}$$

Here the following dimensionless parameters are introduced:

$$n=\frac{k_2}{k_1},\quad N=\frac{2\rho S k_1}{\nu m},\quad v=\nu c k_1 V,\quad \nu=\frac{H_0}{H^2}(Q_b-Q_0). \tag{2}$$

Only four quantities from (1), (2) vary significantly upon the heating of a bed: ρ, ν, k_1, and k_2; by properly allowing for their temperature dependence in Eqs. (1) and (2) it is easy to evaluate the influence of the latter

---

A. V. Lykov Institute of Heat and Mass Exchange, Academy of Sciences of the Belorussian SSR, Minsk. Institute for Problems of Mechanics, Academy of Sciences of the USSR, Moscow.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 35, No. 4, pp. 617-621, October, 1978. Original article submitted November 17, 1977.

0022-0841/78/3504-1163 $07.50

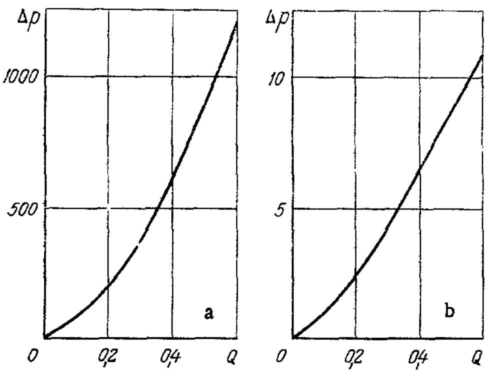

Fig. 1. Hydraulic characteristics of the gas-supply system (a) and the gas-distribution installation used in the theoretical calculations.

on the boundary of the region of stability under the most varied conditions. (Equations obtained under the assumption that the process of gas expansion in the cavity below the grid is isothermal are written above. The equations corresponding to other types of expansion processes do not differ fundamentally from those presented and can easily be obtained using the general method of [1].)

Two modes of bed heating are of practical interest: with a fixed fluidization number W and with a fixed mass velocity q of the fluidizing gas supplied to the apparatus. The first mode reflects the transitional process in the startup (firing up) of the installation, when with an increase in temperature one must reduce the gas velocity in order not to allow the carrying away of material from the bed. The second mode corresponds to the established operation of the apparatus with a constant velocity of the gas supplied to the gas-distribution device.

In the first case the parameters ρ and ν decrease with an increase in temperature. In addition, since the quantity q must be reduced to maintain a constant value of W during heating of the bed, the values of the differential coefficients of resistance of the gas supply channel and the grid also vary, with their rates of variation being determined by the degree of nonlinearity of the respective hydraulic characteristics. These characteristics for the installation used in the experiments are presented in Fig. 1 and can be approximated with sufficient accuracy by the relations

$$\Delta p \approx 2900Q^{1.7},\ \Delta p \approx 24Q^{1.35}\ , \tag{3}$$

if Δp and Q are expressed in N/m^2 and m/sec, respectively.

In this case the calculation begins with a determination of the minimum fluidization velocity corresponding to the given bed temperature (which can be done, for example, by using the well-known Goroshko–Rozenbaum–Todes empirical equation [4]) and the average gas velocity in a column cross section of the apparatus at the given number W. The latter allows one to find the corresponding value of the height H of the bed which it would have in the steady fluidization mode. Then, using the approximate equation

$$Q_b - Q_0 \approx (Q - Q_0)\frac{H}{H - H_0}\ , \tag{4}$$

which is correct when the velocity of the motion of the upper boundary of the bed is neglected in comparison with $Q_b - Q_0$ and $Q - Q_0$ [1], from (2) we obtain the following calculating equation for the parameter ν:

$$\nu \approx \frac{H_0}{H}\,\frac{Q - Q_0}{H - H_0}\ . \tag{5}$$

The velocity of the cold gas supplied to the subgrid chamber, needed to estimate the coefficients k_1 and k_2, is easily expressed through the velocity of the hot gas in the column of the apparatus and the temperature using the relation ρQ = const.

For definiteness the calculations were made in application to an installation with the hydraulic characteristics presented in Fig. 1 [also see Eqs. (3)]. As is easy to see from Fig. 2, they indicate that with an increase in temperature the left boundary of the region of instability [characterized by the quantity v_2 from (1)] shifts toward larger volumes of the subgrid chamber. The right boundary corresponds to unrealistically high

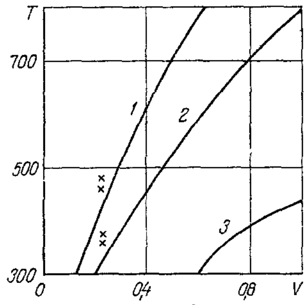

Fig. 2

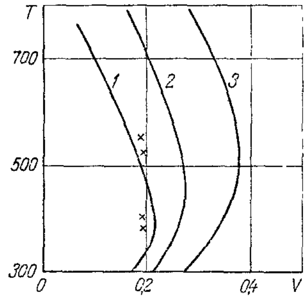

Fig. 3

Fig. 2. Theoretical boundary of the region of instability of the fluidization process in a mode with a fixed fluidization number for a bed of graphite particles (H_0 = 0.1 m, S = 0.0071 m^2, W = 3): 1) d = 0.42; 2) 0.28; 3) 0.16 mm; the region of instability lies to the right of the curves; points) experiment; T, °K; V, m^3.

Fig. 3. Theoretical boundary of the region of instability of the fluidization process in a mode with a constant mass velocity of gas supply for a bed of graphite particles (H_0 = 0.1 m, S = 0.0071 m^2, d = 0.28 mm): 1) Q = 0.2; 2) 0.15; 3) 0.1 m/sec (the values of Q calculated for a cold gas from the given values of q are presented); the region of instability lies to the right of the curves; points) experimental observation of times of generation and cutoff of self-oscillations.

values of V (on the order of 100 m^3) and therefore is not presented. With a decrease in the particle diameter of the bed the disruption of stability and the appearance of self-oscillations occur at a lower temperature (for a given V). It is important that modes are possible when self-oscillations occuring in a cold bed disappear with an increase in temperature.

In the second case, when the velocity of gas supply to the system is fixed, the quantities k_1 and k_2 must be treated as constants. In this case, because of the nonlinearity of the curves of gas expansion, the variation of the parameter ν [for which Eq. (5) is valid as before] has a nonmonotonic character: There is a temperature at which an extremum of ν is reached. The left boundary of the region of instability (Fig. 3) therefore differs considerably from that for the first case considered above (Fig. 2). It is easy to see that the fluidization of the same bed in the same apparatus can be unstable (with realization of a self-oscillatory mode) at low and sufficiently high temperatures but stable in a range of intermediate temperatures. The situation when the apparatus operates in a mode corresponding to just such an intermediate range is of particular interest. Then the spontaneous development of self-oscillations is possible upon the sudden cooling of the bed (owing to the delivery of a new cold batch of granular material to the bed, for example). The self-oscillations promote the mixing and more rapid heating of this batch of material, after which they automatically cease. Thus, it is possible in principle to regulate the time of formation of the self-oscillations (and thereby temporarily intensify the mixing in the bed) by appropriately choosing the operating parameters of the process or by providing for the proper values of k_1, k_2, V, etc., in the construction of the apparatus. The results of the calculations are also given in Fig. 4.

Experiments in both the modes analyzed were conducted on a laboratory installation whose construction is described in [2]. A column of quartz glass 10 cm in diameter was used. A perforated ceramic plate covered by a stainless-steel grid with a through cross section of 4% served as the gas-distribution grid. Graphite of narrow fractions was used as the granular material. The bed was heated by passing an electric current through it; the temperature of the bed was measured with thermocouples and recorded on an oscillograph. The times of generation and cutoff of the self-oscillations were determined from an oscillographic recording of oscillations in the hydraulic resistance of the bed and were well-followed visually. The measurement and regulation of the height of the expanded fluidized bed in the self-oscillatory mode as the temperature increased presented considerable experimental difficulty. But the use of the procedure suggested in [5] made

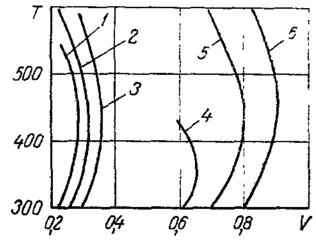

Fig. 4. Calculated boundaries of region of instability in a mode with a constant mass velocity of gas supply [H_0 = 0.1 m, S = 0.0071 m^2; d = 0.42 (1-3) and d = 0.16 mm (4-6)]: 1) Q = 0.19; 2) 0.177; 3) 0.163; 4) 0.067; 5) 0.051; 6) 0.044 m/sec.

it possible to obtain information on the expansion of the bed by measuring the average pressure drops between points located at different levels in the core of the fluidized bed. The error of such measurements was not more than 5-8%. The results of the experiment are shown by the points in Figs. 2 and 3. There is acceptable agreement between the results of the numerical (based on the theory in [1]) and laboratory experiments. Thus, the proposed method of estimating the boundaries of the region of stability of the fluidization process can be fully used in an analysis of the operation of real apparatus containing heated fluidized beds.

NOTATION

c = M/RT; M	is the molecular weight of gas;
R	is the gas constant;
d	is the particle diameter;
H	is the bed height corresponding to the steady mode of fluidization;
k_1, k_2	are the coefficients of hydraulic resistance of gas-supply channel and gas-distribution grid;
N, n	are the parameters defined in (2);
Δp	is the pressure drop;
Q	is the average gas velocity;
Q_b	is the gas velocity in the bubble phase;
q	is the mass velocity of gas supply to the system;
S	is the cross-sectional area of column;
T	is the temperature;
V	is the volume of the subgrid cavity;
v	is the dimensionless volume;
W	is the fluidization number;
ν	is the parameter defined in (2) and (5);
ρ	is the gas density; the zero subscript refers to the state of minimal fluidization.

LITERATURE CITED

1. V. A. Borodulya, Yu. A. Buevich, and V. V. Zav'yalov, Inzh.-Fiz. Zh., 31, 410 (1976).
2. V. V. Zav'yalov, in: Heat and Mass Exchange in Two-Phase Systems with Phase and Chemical Transitions [in Russian], Inst. Teplo- Massoobmena, Minsk (1976).
3. V. A. Borodulya, Yu. A. Buevich, and V. V. Zav'yalov, Inzh.-Fiz. Zh., 32, 45 (1977).
4. V. D. Goroshko, R. B. Rozenbaum, and O. M. Todes, Izv. Vyssh. Uchebn. Zaved., Neft' Gaz, No. 1, 125 (1958).
5. D. M. Galershtein, S. S. Zabrodskii, A. I. Tamarin, V. N. Borisenko, V. M. Shuklina, and T. É. Fruman, in: Heat and Mass Transfer in Processes of Heat Treatment of Disperse Materials [in Russian], Inst. Teplo- Massoobmena, Minsk (1974).