EXPANSION AND POROSITY OF AN INHOMOGENEOUS FLUIDIZED BED

V. I. Ivanyutenko, N. V. Antonishin, and V. S. Nikitin

UDC 66.096.5.001

Results of an experimental investigation of porosity and expansion of thin fluidized beds are presented and empirical equations are proposed for calculating the thickness of the bed.

In order to solve problems of internal and external heat transfer and thermal conductivity when finely dispersed particles are fluidized by a gas, it is necessary to know the characteristics of the expansion of the bed and of the change in the porosity over the height of the bed. As has been established by the work of many researchers, the thermal and mass-transfer characteristics of fluidized systems depend on the particle concentration.

It has still not been established how to define the expansion height. The height of the bed is sometimes taken as the visually observed thickness, the strongly fluctuating total magnitude of its dense region, and the region where particles are ejected. There are approaches that are related to the change in the drag of the bed [1]. It is possible to define the boundary of the expanded bed as the height beyond which less than 3% of the solid phase of the bed is present [2]. It is clear that different percolation rates of the gas, with other characteristics of the fluidized system remaining the same, will lead to different porosity at the height of expansion, determined by the methods indicated.

It is preferable to use the magnitude of the porosity of the fluidized bed as the criterion for the choice of the effective thickness in heat-transfer processes. Starting with a specific process, it is possible to know in advance the magnitude of the limiting useful porosity in this case. And, since the particle concentration in a fluidized bed varies over its thickness, the boundary of the bed should be chosen as the height where the porosity attains this value.

We have attempted to study the behavior of the expansion of a bed and to relate this behavior to the distribution of the solid phase in a fluidized system.

There exist [2] empirical equations that describe the expansion of thick layers consisting of large particles, requiring in separate cases knowledge of a table of coefficients. But, in spite of the energy-related advantages of so-called thin beds and beds consisting of small particles, which are inherently much less inhomogeneous in the hydrodynamic sense, there are no satisfactory correlations between the expansion and parameters of such systems in the literature.

In order to investigate the expansion of the bed, we made use of motion pictures of the fluctuations in the upper boundary of the bed [2] in a setup with a transparent wall, whose dimensions in the plane were 0.31×0.065 m. The gas distribution network, consisting of a multilayer grid, provided ideal fluidization over the entire area of the bed for different gas velocities. The height of the stationary settled bed consisting of particles with a narrow fractionated composition varied from 0.01 to 0.05 m.

In the experiments, we used particles of sand and magnesite, whose characteristics were determined experimentally.

The motion pictures that were taken were projected with threefold magnification on the scale field, on which from each motion-picture frame a profile of the upper fluctuating boundary of the layer was marked. After processing 15-20 motion pictures corresponding to a single regime, we counted n intersections (in a definite interval of bed thicknesses) of the wavy line of the upper boundary with uniformly spaced vertical lines. Since the fluctua-

---

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 41, No. 3, pp. 470-475, September, 1981. Original article submitted June 11, 1980.

 0022-0841/81/4103-0982$07.50

TABLE 1. Probability for the Distribution of Instantaneous Values of the Height of a Fluidized Inhomogeneous Bed (sand, ρ_p = 2700 kg/m³, d = 0.250-0.315 mm, h_0 = 10 mm)

w, m/sec	Height of bed, mm							
	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5
0,314	0,02	0,066	0,148	0,264	0,212	0,144	0,112	0,06
0,544	0,008	0,014	0,046	0,134	0,148	0,176	0,148	0,136
0,760				0,01	0,042	0,088	0,106	0,136
	17,5	18,5	19,5	20,5	21,5	22,5	23,5	24,5
0,314	0,032	0,01	0,016					
0,544	0,09	0,066	0,028	0,018	0,014			
0,760	0,156	0,130	0,120	0,104	0,086	0,058	0,03	0,018

tions of the upper boundary of the bed are of a random nature, they can be estimated with the help of statistical methods.

Table 1 presents typical histograms of the positions of the upper boundary, which differ from the normal distribution law [2, 3]. The distributions obtained are not symmetrical relative to their to maximum probability values due to the fact that the fluctuations of the upper boundary of the bed are bounded, as if supported from below by the grid, while there is no such limitation from above, and the probability for finding the upper boundary, surges, and blowouts of the bed at a quite high height is different from zero.

All experimentally obtained histograms were approximated using the least-squares method with a computer by the empirical function

$$\gamma = \frac{n}{m} = a\,(h_x - l)^{b} \exp\left[c\,(h_x - l)\right]. \tag{1}$$

For these curves of the distribution over the parameters a, b, c, and l found in each specific fluidization regime, we calculate from Eq. (1) two height levels of the bed: the first level h_L corresponds to the lower height of the expanded bed, for which the probability $\gamma \geq 0.03$; the second height h_U corresponds to the upper position of the fluctuation boundary of the bed, $\gamma \leq 0.03$. The zone between them corresponds to heights where the fluctuating upper boundary of the bed occupies with probability $\gamma > 0.03$ all of its intermediate values between h_L and h_U. Below the first and above the second levels of heights, the probability for finding the upper boundary of the bed can be assumed to be close to zero.

Figure 1 shows the experimental data on the expansion of the inhomogeneous bed as a function of the fluidization numbers for different heights of the stationary fill for three fractions of the material. A qualitative analysis of the experimental points with identical fluidization numbers leads to the following conclusions:

1) for large Ar numbers, the expansion h_x/h_0 of the bed is greater with identical heights of the stationary fill;

2) as h_0 increases with Ar = const, the relative expansion decreases; beds with lower initial heights expand more than higher beds.

For large h, the difference between the levels h_L and h_U decreases. For thick beds, it may be expected that the ratio of this difference to the overall height of the bed becomes insignificant, and for these beds the magnitude of the expansion can be taken as the average level of the upper boundary of the bed.

Analysis of the experimental data using the least-squares method yielded empirical dependences for the expansion of the bed. For the lower level of the fluctuating upper boundary,

$$\frac{h_L}{h_0} = 0.0768\,\frac{\mathrm{Ar}^{0.122}}{h_0^{0.298}}\,N^{(1-\varepsilon_0)}\,, \tag{2}$$

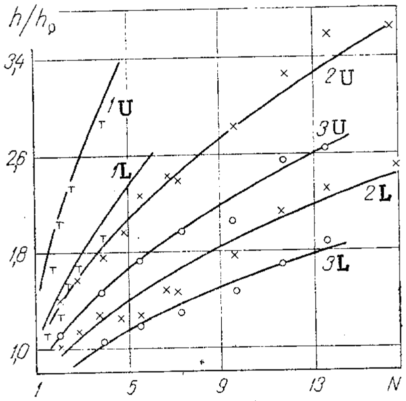

Fig. 1

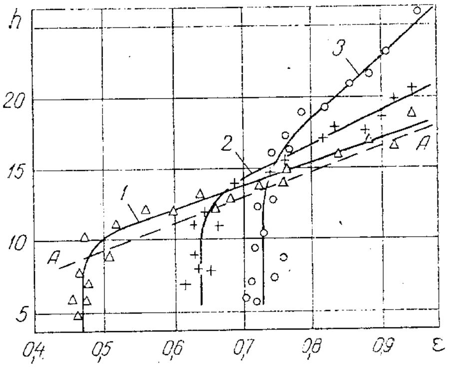

Fig. 2

Fig. 1. Experimental data on expansion of a bed of sand as a function of the fluidized numbers (L, U indicate the lower and upper levels): 1) d = 0.572 mm, h_0 = 0.01 m; 2) 0.189 and 0.01; 3) 0.189 and 0.02.

Fig. 2. Porosity distribution over the thickness of a fluidized bed of sand, ρ_p = 2700 kg/m³, d = 0.326: 1) w = 0.314 m/sec; 2) 0.544; 3) 0.76. h, mm.

and for the upper level,

$$\frac{h_U}{h_0} = 0{,}112\,\frac{\mathrm{Ar}^{0,122}}{h_0^{0,299}}\,N^{(1-\varepsilon_0)}. \tag{3}$$

The values of the bed thickness, calculated from these equations, for Archimedes number varying in the range $100 \leqslant \mathrm{Ar} \leqslant 100{,}000$, coincide with the experimental data obtained to within ±7%. Comparison with known [2] relations showed that independent of the range of variation of Ar and h_0, Eq. (2) agrees with them with a maximum error of 20% for fluidization numbers N = 9-10. For smaller N, the error decreases.

The total porosity at a given layer was determined by taking successive samples at two levels at intervals of 1 mm using the same setup with the same fluidization regimes as in the motion-picture experiments. The sampler with thin vertical walls, after loading the lower open part onto the given level in the bed, was covered by a flexible shutter, whose rate of motion in the horizontal plane was greater than the maximum velocity of the fluidizing agent.

The experimental data on the distribution of porosity are presented in Fig. 2. The continuous lines show graphs of the polynomials with whose help the experimental points were approximated. It is evident that in thin fluidized beds there are zones with constant porosity from the gas distribution network to some level. These zones are different for different fluidization rates both over the thickness as well as with respect to the absolute value of the porosity. Above the dashed line A—A, there is a zone with surges of the upper boundary of the bed: this is the zone with increasing porosity; in this zone, the particle concentration decreases linearly with thickness.

Figure 3 shows on an identical scale along the thickness axis curves approximating (according to Eq. (1)) the histograms of the distribution of the upper boundary of the expanded bed (lines A) and curves showing the porosity distribution over the thickness of this bed (B) for identical fluidization regimes. The upper line corresponds to a porosity of ε = 0.97, while the lower line corresponds to a probability of γ = 0.03. This dashed line delineates on the probability distribution curves for the upper boundary of the bed the first and second zones with levels h_L and h_U. Levels where the porosity of the bed is ε = 0.97, while the probability γ = 0.03, coincide to within ±5% both along the porosity curves and for the upper (right) part of the histograms of the distribution with identical fluidization rates. The levels of the lower (left) part of the histograms, where the probability γ = 0.03, also coincide with the levels where the zones of constant porosity terminate. A comparison of the experimental data leads to the conclusion that the histograms of the distribution of the upper boundary of the expanded bed at probability levels $\gamma \geqslant 0.03$ correspond to a zone with decreasing porosity of the thin fluidized bed.

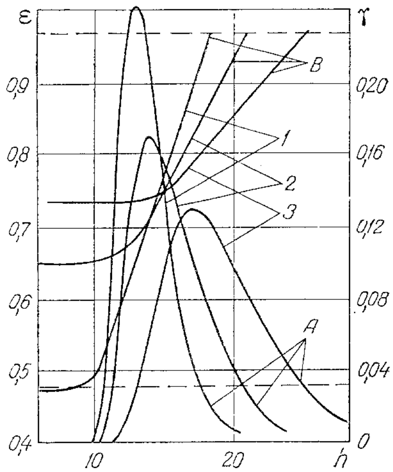

Fig. 3. Comparison of the approximating lines A for the distribution of instantaneous flows of the bed height with the computed lines B of the porosity distribution over the bed height (sand, ρ_p = 2700 kg/m³, d = 0.326 mm): 1-3) see Fig. 2.

It is useful to relate the geometrical parameters (zone heights) of the expanded bed to the total porosity at each level in the bed.

Assume that we have a stationary settled bed of height h_0, whose volume is V_0 and porosity is ε_0. For a gas percolation rate greater than the initial fluidization rate, the bed expands and in accordance with previously obtained results, the first lower zone with constant porosity up to the level h_L and the second upper zone with increasing porosity to level h_U can be separated out in it. Let us assume that the porosity in the first zone is constant everywhere from h = 0 to h_L and equal to ε_L, while at the level h_U, ε = 1. Let us assume that the average porosity in the second zone equals

$$\varepsilon_U = \frac{\varepsilon_L + 1}{2} .$$

We write the equation for the distribution of the solid phase in the volumes of the segments singled out

$$V_0^p = V_L^p + V_U^p . \tag{4}$$

Expressing the porosity in them in terms of the geometric volumes of the zones and in terms of the volumes of the solid phases found in them

$$\varepsilon_L = \frac{V_L - V_L^p}{V_L} , \quad \varepsilon_U = \frac{V_U - V_U^p}{V_U}$$

and substituting into (4), we obtain

$$V_0^p = V_L (1 - \varepsilon_L) + V_U (1 - \varepsilon_U). \tag{5}$$

Transforming to the levels determined by the motion pictures from Eqs. (2) and (3), and assuming that

$$V_L = dF_l \, h_l , \; V_U = dF_l \, (h_U - h_L),$$

$$V_0^p = dF_l \, h_0 - \varepsilon_0 dF_l \, h_0,$$

we obtain an expression for the magnitude of the porosity in the first lower zone in terms of the geometric parameters of the expanded bed and the porosity of the stationary fill:

$$\varepsilon_L = \frac{h_L + h_U - 2h_0 (1 - \varepsilon_0)}{h_L - h_U} . \tag{6}$$

The porosity in the second upper zone of the fluidized bed at any level is determined in terms of the porosity of the first zone:

$$\varepsilon_x = \frac{h_x(1-\varepsilon_L) - h_L + h_U\varepsilon_L}{h_U - h_L}. \quad (7)$$

Thus, given fixed predetermined values of the porosity ε_D in the second zone, it may be assumed that the effective height of the expanded bed will be the level where the porosity attains this magnitude. The numerical value of the height of the bed is calculated from the equation

$$h_D = \frac{\varepsilon_D(h_U - h_L) + h_L - h_U\varepsilon_L}{1-\varepsilon_L}; \quad (8)$$

the quantities entering into this expression are obtained from Eqs. (2), (3), and (6).

With the help of the experimental data, we calculated the values of h_D of the height of the bed using Eqs. (6) and (8), where the porosity $\varepsilon = 0.90$. Least squares analysis of all of the experimental points provided an empirical function for the expansion of the bed to a level h_D with limiting porosity $\varepsilon_D = 0.90$:

$$\frac{h_D}{h_0} = 0.0993 \frac{\mathrm{Ar}^{0.122}}{h_0^{0.292}} N^{(1-\varepsilon_0)}, \quad (9)$$

which describes the experimental results to within ±5%.

NOTATION

γ, probability for finding the upper boundary of the bed at a given level; a, b, c, and l, approximating coefficients; h, height of the bed, m; N, fluidization number; ε, porosity of the bed; V, volume; w, velocity of the fluidizing agent, m/sec; Ar, Archimedes number. The indices are as follows: 0, L, V, stationary bed and the lower and upper levels of the fluidized bed, respectively; p, particles; x, volume from which the sample was taken.

LITERATURE CITED

1. S. S. Zabrodskii, High-Temperature Installations with a Fluidized Bed [in Russian], Énergiya, Moscow (1971).
2. N. A. Shakhova, L. S. Aksel'rod, and V. E. Kats, "Investigation of the expansion of an inhomogeneous bed," in: Application of a Fluidized Bed in the Metallurgical Industry [in Russian], No. 21, Donetsk (1970), pp. 30-41.
3. N. A. Shakhova and V. E. Kats, "Expansion of an inhomogeneous fluidized bed," Khim. Prom., No. 5, 35-57 (1975).