Journal of Engineering Physics and Thermophysics, Vol. 69, No. 5, 1996

CALCULATION OF THE HEIGHT OF THE SEPARATION ZONE OF A POLYDISPERSE FLUIDIZED BED

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We obtained experimental data on the heights of the space above a polydisperse fluidized agloporit bed. On the basis of Fr and Ar numbers, we generalized the available data on the values of the critical height of the separation zone in beds of mono- and polydisperse particles.

As is known, a characteristic feature of an inhomogeneous fluidized bed (FB) is the presence of a rather voluminous space above the bed into which the particles of the bed are swept. The existing models of entrainment, for example [1-4], are based on the established experimental fact: the entrainment of particles is formed by gas bubbles emerging from the bed. These bubbles form local inhomogeneities of gas flow on the surface that lead to powerful entrainment of particles.

The literature cites rather numerous experimental data on measurements of H_c in beds of monodisperse particles [5-8]. In [5] an important fact was revealed experimentally: the dependence of the separation zone height on the diameter of particles at the same value of excess interstitial gas velocity is nonmonotonic, and in the range $d \approx 0.6-0.8$ mm the falling function $H_c(d)$ has an inflection and increases appreciably with an increase in d. In our opinion, this is easily explained by the existing difference in the flows of the gas in bubbles that pass through the beds of small ($d < 0.6$ mm) and large ($d > 0.8$ mm) particles [2, p. 110]. As shown in [9], the velocity of a gas flow through a bubble in beds of large particles attains substantial values of the order of $(7-10)u_0$; this leads to powerful ejections of particles raised by the bubble dome in the space above the bed in correspondence with the entrainment mechanism described in [4]. A different situation is observed in beds of small particles, where the gas flow velocity in a bubble is equal to $(2-3)u_0$[2] and is relatively small because of the smallness of u_0. We note that in such beds appreciable ejections of particles can probably be formed only as a result of relatively rare events of the coalescence of several bubbles near the bed surface and formation of specific cumulative funnels into which the gas from the emulsion rushes [1]. The foregoing points to the impossibility of correlating experimental data on H_c in beds of small and large particles by a single monotonic relation. In this connection we should note an unsuitable choice of the correlating function in [5]:

$$H_c/D = (H_0/D)^{0.5}\,(m\,(u - u_0)/u_0 + n)\,, \tag{1}$$

where the coefficients m and n should be selected every time for the conditions of specific experiments. This does not actually allow the use of relation (1) in computational practice.

In polyfractional beds, where, generally speaking, there are several limited separation zones of height H_i (by the number of fractions with $d_i > d_t$),* there are much fewer experimental data [10, 11], and no relations are available that could be used for estimating the value of the critical height of the separation zone H_c.

The experiments were run on a test rig [12] that had interchangeable side-bars of two types: circular ones with a diameter of 0.7 m and semicircular ones of the same diameter ($D_{\rm eff} \approx 0.5$ m). The circular column had a

* The quantity d_t is determined from the well-known Todes formula $\mathrm{Re}_t = \mathrm{Ar}_t/(18 + 0.6(\mathrm{Ar}_t)^{1/2})$.

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the Academy of Sciences of Belarus," Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 69, No. 5, pp. 816-820, September-October, 1996. Original article submitted July 28, 1994.

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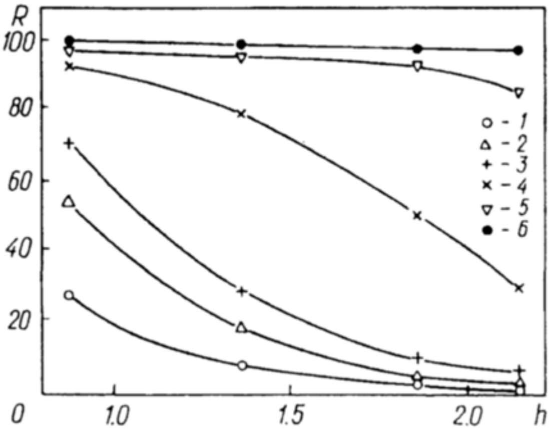


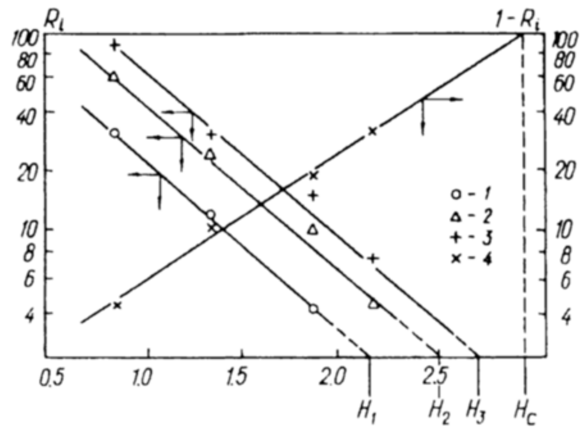


Fig. 1. Change of the content of fractions over the height of the space above the bed (H_0 = 0.37 m; d_t = 0.29 mm, u = 1.9 m/sec, cap grid): 1) d_i = 2.5; 2) 1.0; 3) 0.63; 4) 0.4; 5) 0.315; 6) 0.2 mm. R, %; h, m.

Fig. 2. A procedure for calculating the height of the space above the bed (H_0 = 0.37 m; u = 2.1 m/sec, cap grid): 1) d_i = 2.5; 2) 1.0; 3) 0.63; 4) 0.4 mm. R_i, %.

cap gas distributor, while the gas distributor of the semicircular column was lamellar [13]. Samples of disperse material were taken from the space above the bed by a sampling apparatus consisting of a system of "small ladles" located on different levels. The material of the bed was agloporit of a wide disperse composition [11]. Fluidization was produced by air at a temperature of 15–20°C. The values of the density and porosity of the fixed filling and of the minimum fluidizing velocity are: ρ_s = 1640 kg/m^3; ε_0 = 0.40; u_0 = 1.05 m/sec. As the space above the bed is limited, we could measure directly the heights of the flight of particles only for d_i = 2.5 mm. For smaller fractions the values of H_i and H_c were measured indirectly. From the graphs of the fractional composition of the ejections at different heights (Fig. 1) we could see that these curves changed the sign of their curvature with the change in the values of d_i. In this connection we suggested that the obtained data be represented in semilogarithmic coordinates (ln R, h for the functions with $d^2R/dh^2 < 0$; ln $(1 - R)$, h for the functions with $d^2R/dh^2 > 0$) (Fig. 2). The linear character of the change of such dependences makes it possible to reliably determine the corresponding values of H_i and H_c by extrapolating straight lines up to their intersection with the abscissa axis. Data obtained in this way are presented in Fig. 3.

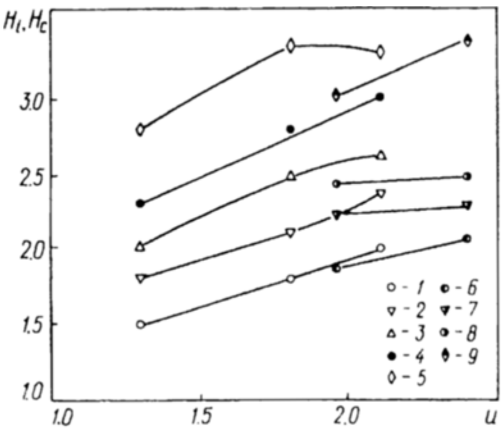
To analyze and correlate our data and those available in the literature, we used a concept suggested by us earlier in [14] for simulating the processes of transfer in inhomogeneous fluidized beds within the framework of similarity theory. It is established that the two-phase nature of a fluidized bed leads to the existence of two criteria that are generalized characteristics of a discrete and an emulsion phase, respectively, namely, Fr and Ar. As shown in [14], in general the transfer characteristic of the bed (Fb) is defined by the equation

$$\mathrm{FB} = \psi\,(\mathrm{Fr}, \mathrm{Ar}, H_0/D, h/H_0, \rho_s/\rho_f, c_s/c_f)\,. \tag{2}$$

In our case, to determine the height of the space above the bed the number of the arguments of the function ψ should be supplemented with the number Re that characterizes the motion of a particle above the bed and to remove the simplexes h/H_0 and c_s/c_f:

$$\mathrm{FR} = \psi\,(\mathrm{Fr}, \mathrm{Ar}, \mathrm{Re}, H_0/D, \rho_s/\rho_f)\,. \tag{3}$$

The number of arguments of the function ψ can be reduced. Taking into account the fact that the gas velocity is already involved in the expression for Fr and that the particle diameter is incorporated into the expression for Ar, we can neglect in a first approximation the effect of the number Re. To analyze experiments carried out at normal temperatures and pressures, we may also neglect the effect of the simplex ρ_s/ρ_f (of course, provided that



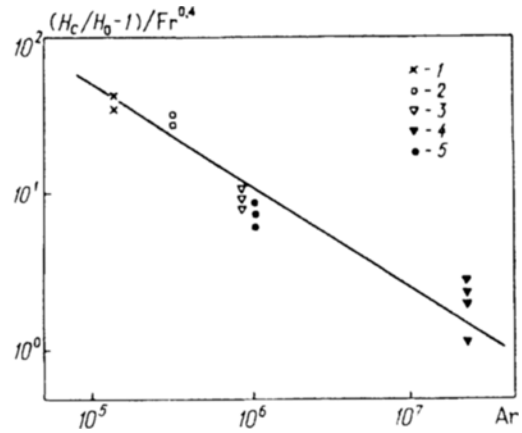


Fig. 3. Dependence of the height of space above the bed on the interstitial velocity: 1) $d_i = 2.5$; 2) 1.0; 3) 0.6; 4) 0.4 mm; 5) d_t^* (cap grid, $H_0 = 0.40$ m); 6) $d_i = 2.5$; 7) 1.0; 8) 0.4 mm; 9) d_t^* (lamellar grid, $H_0 = 0.36$ m). H_i, H_c, m; u, m/sec.

Fig. 4. Generalization of experimental data on the height of the space above the bed in beds of large particles: 1) $d = 0.967$; 2) 1.33; 3) 1.85; 4) 5.6 mm [5]; 5) $d = 3.16$ mm [8]; solid line, according to Eq. (6).

the values of ρ_f and ρ_s do not change appreciably). Such assumptions greatly simplify expression (3) and reduce it to the form

$$H_c/H_0 - 1 = \psi\,(\mathrm{Fr}, \mathrm{Ar}, H_0/D)\,. \tag{4}$$

Obviously, in formula (4) the numbers Fr and H_0/D reflect the effect of the exit conditions of bubbles (and, consequently, of solid particles) from the bed (in the first place, of their velocities), and the number Ar allows for the character of particle motion in the space above the bed.

We shall generalize the experimental data in conformity with formula (4), first for monodisperse and then for polydisperse beds.

Monodisperse Beds of Small Particles. The processing of experimental data of [5] for corundum particles with $d = 0.134$; 0.229, and 0.317 mm led to the relation

$$H_c/H_0 - 1 = 82\,(\mathrm{Fr}/\mathrm{Ar})^{0.25}\,(H_0/D)^{-0.5}\,. \tag{5}$$

The standard deviation of the experimental data from those calculated by relation (5) is 26%.

Monodisperse Beds of Large Particles. Similar processing of the results of experiments of [5, 8] for beds of corundum particles with $d = 0.967$, 1.33, 1.85, and 5.6 mm made it possible to establish the relation

$$H_c/H_0 - 1 = 4.8 \cdot 10^4\,\mathrm{Fr}^{0.4}\,\mathrm{Ar}^{-0.6}\,, \tag{6}$$

which describes the experimental data with a standard deviation of 21% (Fig. 4). It is of interest to note that earlier we obtained similar and also differing dependences on Fr and H_0/D for a phenomenon that is closely associated with the motion of bubbles in a bed, i.e., the expansion of monodisperse beds of small and large particles: $H/H_0 - 1 = 0.7(H_0/D)^{0.5}\mathrm{Fr}^{0.33}$ [15] (small particles); $H/H_0 - 1 = 0.54\mathrm{Fr}^{0.54}$ [9] (large particles).

Polydisperse Beds. The structure of relation (4) is such that it can be easily extended to the case of polydisperse beds:

$$H_i/H_0 - 1 = \psi\,(\mathrm{Fr}, \mathrm{Ar}_i, H_0/D)\,. \tag{7}$$

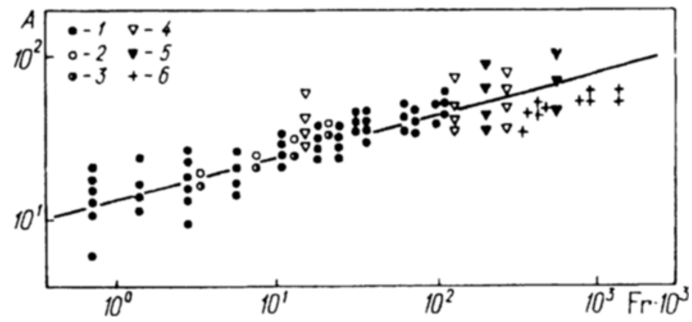


Fig. 5. Generalization of experimental data on the height of the space above the bed (H_i and H_c): 1) [5] (d = 0.317 mm); 2, 3) [5] (d = 0.134 and 0.229 mm, respectively); 4, 5) our data for circular and semicircular columns, respectively; 6) [10]; solid line, according to Eq. (8). $A \equiv (H_i/H_0 - 1)\,/\,\mathrm{Ar}_i^{-0.25}(H_0/D)^{-0.5}$.

Here, as the critical height of the space above the bed one should consider the quantity $H_c = \max\{H_i\}$, provided that $d_i > d_t$. It is important to note that Eq. (7) contains two different diameters of particles: the Fr number involves the velocity of the onset of fluidization of a polydisperse bed, which is determined by the equivalent diameter of the particles of the bed $d_{\mathrm{eff}} = \Sigma\, d_i\eta_i^{*}$ [16], while, conversely, the Ar_i number involves the diameter of the fraction d_i. The data obtained by us on the basis of such concepts and those available in the literature [10] were processed by relation (7). We found that the exponents of the numbers Fr and Ar_i were very close to the corresponding values in formula (5). Therefore, the data for polydisperse beds were processed together with the earlier mentioned experimental data for H_c in beds of small monodisperse particles. We obtained a relation that virtually coincides with Eq. (5):

$$H_i/H_0 - 1 = 85\,(\mathrm{Fr}/\mathrm{Ar}_i)^{0.25}\,(H_0/D)^{-0.5}\,, \tag{8}$$

which describes the experimental values for H_c and H_i with a mean-square spread of 30% (Fig. 5). We verified formula (8) in the following ranges of parameters: $0.2 \le D \le 1.95$ m; $0.05 \le H_0 \le 0.4$ m; $0.2 \le u - u_0 \le 2.4$ m/sec. We emphasize that the value of the critical height of the separation zone of a polydisperse bed H_c is the greatest of the values of H_i calculated from relation (8) and corresponds to the size of the sieve d_t^{*}.

The fact of the close similarity between the laws governing entrainment in beds of small monofractional and polyfractional particles requires a reasonable physical explanation. In our opinion, the main reason for this is as follows. It is known [17] that when a large-size granular material is fluidized by a gas-suspension flow, the system, because of the increase in ρ_f and c_f (compared with a pure gas), behaves in many respects as a pressurized bed. But such a bed is characterized by greater inhomogeneity of the structure (greater expansion, a sharp decrease in bubble size, etc. [18]). Naturally, this decreases the magnitude of the gas flow through the bubble and decreases the intensity of the entrainment of particles from the bed. A polydisperse bed of a wide granular composition, in which small fractions are filtered in the gaps between large ones, is in a sense analogous to a bed of large-size material fluidized by a gas suspension. Probably, in such a system one also observes a substantial expansion of the emulsion phase, and this leads to redistribution of the gas flow (the gas velocity in the emulsion increases and, correspondingly, the velocity in the bubbles decreases, which mainly is responsible for entrainment). Precisely this explains the fact that at the rather high equivalent diameters of particles in polydisperse beds investigated (d_{eff} = 2.45 mm [10] and d_{eff} = 3.5 mm for the agloporit used in the present work) the latter generate entrainment that

* Neglecting the abrasion of the material, it is admissible to analyze the situation when there are no particles in the bed with $d_i < d_t$ that are irretrievably entrained from it.

has regularities characteristic of monodisperse beds of small particles, where the velocity of gas in bubbles is also relatively small (see above).

In conclusion we will emphasize that relations (6) and (8) directly (the Fr number) take into account the cause-and-effect relationship between the phenomena of the ejection of bubbles onto the bed surface and entrainment of particles into the space above the bed. Formulas (6) and (8) have an extremely simple form and are convenient for estimating H_c in industrial fluidized-bed apparatuses.

NOTATION

c_f, c_s, specific heats of gas and particles; d_i, diameter of particles of the i-th fraction; d_t^*, size of standard cell of sieve closest to d_t ($d_t^* > d_t$); d, diameter of monofractional particles; D, diameter of the apparatus; g, free fall acceleration; H, H_0, heights of bed at interstitial gas velocities u and u_0; h, height over gas-distribution grid; H_i, maximum height of the flight of particles of diameter d_i; H_c, critical height of the space above a bed ($H_c = \max\{H_i\}$, reckoned from gas distribution); R_i, residual on sieve with cell d_i; u, u_0, interstitial velocity and velocity of onset of fluidization; ν, kinematic viscosity of gas; ρ_f, ρ_s, density of gas and particles; η_i, mass fraction of particles of size d_i; $\mathrm{Ar} = gd^3(\rho_s/\rho_f - 1)/\nu^2$, Archimedes number; $\mathrm{Ar}_i = gd_i^3(\rho_s/\rho_f - 1)/\nu^2$; $\mathrm{Ar}_t = gd_t^3(\rho_s/\rho_f - 1)/\nu^2$; $\mathrm{Fr} = (u - u_0)^2/gH_0$, Froude number; $\mathrm{Re} = ud/\nu$, Reynolds number; $\mathrm{Re}_t = ud_t/\nu$.

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