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PARTICLE GRANULATION IN FLUIDIZED BED

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A mechanism of particle granulation in a wet fluidized bed is proposed on the basis of experimental data, and test calculations are performed.

The rheological transformations of a wet disperse medium under the action of vibration underlie the intensification of such technological processes as filtration, drying, granulation, and transportation [1]. Common to these processes is the granulation of material in a wet grainy medium moving under the action of spatial vibration. Granulation has been most investigated at elements introduced in the form of specially prepared small lumps [2] or liquid drops [3-5], which determines the disperse composition of the granules obtained. However, these experiments do not address the question of the granulometric composition of the filler with uniform moisture content of the particles over the whole layer in a vertically vibrating container, corresponding, in particular, to drying in a fluidized bed (Fig. 1a). In determining the granulometric composition of a uniformly wet mixture in a vibrating container, serious methodological difficulties arise. Therefore, taking into account that the size of the new particles in vibrogranulators of various types is ~10^{-3} m [5-8], aerodynamic forces in a fluidized bed of such particles may be neglected [3], and the gas-permeable bottom of the container is replaced by a set of screens (diameter 200 mm) from a standard sifting unit. This system is an analog of a fluidized unit with convective heat-carrier supply. However, special investigations show that a similar granulometric composition of the disperse mass is also observed in apparatus with a gas-permeable bottom, which means that the results obtained may be extended to apparatus with conductive heat supply.

The error of the given method is determined by the ratio of granulation and screening rates. Since the relaxation time of the capillary processes (~10^{-3} sec)* at a distance of

*Estimate based on the data of [9].

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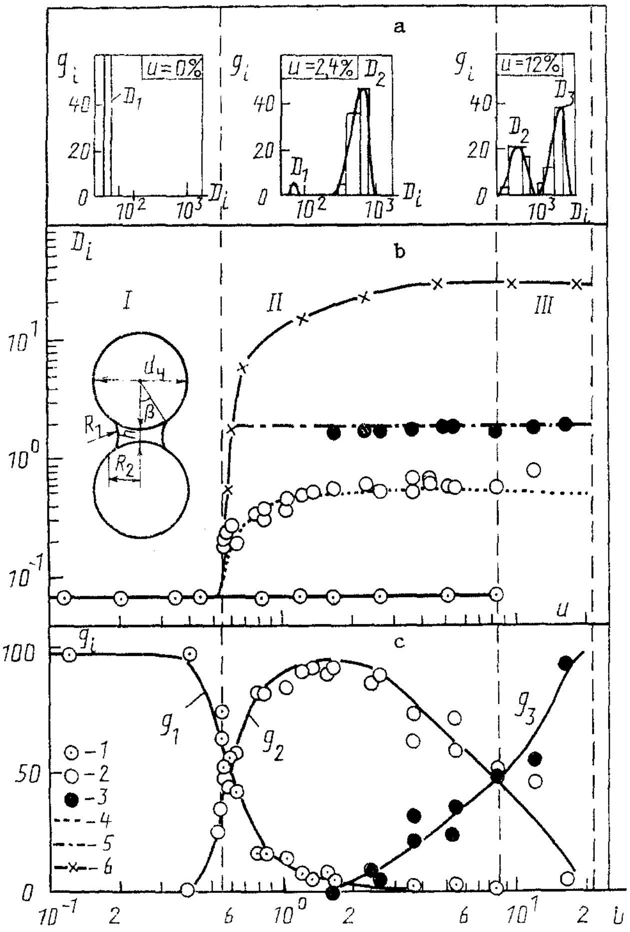

Fig. 1. Dependence of granule diameter (a, b) and their mass concentration (c) on the moisture content of the vibrating filler: 1, 2, 3) D_1, D_2, D_3 in Fig. 1a; 4, 5, 6) calculation from Eqs. (11), (12), and (13), respectively; f = 20 Hz; K = 3.2; d_p = 72 μm; corundum; h/d_p = 0.05; u, g_i, %; D_i, μm.

the order of the diameter of the initial filler grains is small in comparison with the periodicity of vibration (~10^{-2} sec), it may be supposed that the redistribution of moisture in the course of granulation is practically instantaneous. Then, the length of the experiment is determined by the screening time of the mixture under the action of vertical vibration with insignificant dehydration of the material. Observations show that the optimal time of the experiment guaranteeing stabilization of the granulometric composition with pronounced loss of moisture content is around 5 min. Similar time estimates are encountered in the description of other methods of vibrational granulation [5-8]. Preliminarily moistened particles of small corundum fractions (d_p = 30-700 μm) and glass balls (d_p = 2.7, 4 mm) are investigated at a frequency f = 20 Hz with relative acceleration of the vibration K = 0-10.

At a moisture content of 0-20%, three characteristic granule sizes, each corresponding to a definite type of binding of the water with the material, may be distinguished. The first, D_1, is the particle diameter of the material d_p, and moisture is present in the form of a thin adsorption layer (physicochemical binding [10, 11]). In granules corresponding to D_2, the moisture is present in the form of liquid bridges at the contact points between the particles (physicomechanical binding [10, 11]). The projecting sections of the grains forming the granule are coated with an absorption film, as before. In granules corresponding to D_3, the liquid bridges combine together, forming unbound liquid [9]. On the basis of the predominant content of granules corresponding to a definite mode of liquid binding, the dependence of the new particles on the mean relative moisture content of the filler U may also be divided into three regions (Fig. 1). In each region, granules of moisture content u_i not corresponding to the predominant mean moisture content of the layer may be present (Fig. 1), which may be due to a nonuniform preliminary distribution of moisture over the bed volume or to defects of liquid redistribution in vibrogranulation. The distribution with respect to fractions is practically always bimodal (D_1 and D_2, D_2 and D_3; Fig. 1), corresponding to disperse granulated material [9, 12].

In the given system, the granule size is determined from the condition that the inertial forces and the autohesional coupling forces between the grains are equal

$$F_{in} = F_{co} \tag{1}$$

In order of magnitude, the inertial force of a granule at the bottom is

$$F_{in} = \frac{\pi D_i^3 \rho_g}{6(1 - U_i)} g(1 + K), \tag{2}$$

where D_i is the desired size of the particles formed; $\rho_g = \rho_p(1 - \varepsilon)$ is the granule density; ρ_p is the density of the grain material; ε is the porosity of the granule; U_i is the moisture content with respect to the total mass f of the aggregate; g is the acceleration due to gravity.

The value of F_{co} depends on the dominant form of moisture and the structure of the bed. According to observations, two cases may be distinguished.

A. The filler is in the fluidized state and has a granulated structure; the moisture is concentrated at the contact points between the particles (capillary form of moisture). In this case, the granules correspond to mode D_2.

B. The bed has the same structure as in case A but the pores of the particles are completely filled with liquid, which corresponds to granules of mode D_3.

The formula for the coupling force in case A is obtained on the basis of the concept of granule destruction by the husking mechanism (systematic breakaway of individual particles), which is the most probable with capillary moisture (case A_1)

$$F_{co} = F_d. \tag{3}$$

In the general case, the coupling force F_d between two adjacent grains (spheres of identical size) consists of two components [13]: the attractive forces from the surface tension of the liquid phase

$$F_{at} = \sigma\pi d_p \sin\beta \sin(\beta + \delta) \tag{4}$$

and the capillary coupling force

$$F_{ca} = \sigma \frac{\pi d_p^2}{4} \sin^2\beta \left(\frac{1}{R_1} - \frac{1}{R_2}\right), \tag{5}$$

where δ is the limiting angle of wetting; σ is the surface tension of the liquid phase; h, R_1, R_2, and β are shown in Fig. 1b. In the case of a lyophilic particle surface, $\delta = 0$, and from simple geometric considerations

$$R_1 = \frac{d_p(1 - \cos\beta) + h}{2\cos\beta}, \tag{6}$$

$$R_2 = \frac{d_p + h}{2} \operatorname{tg}\beta - R_1. \tag{7}$$

The angle β is determined by the moisture content and structure of the granule. As is known, vibrogranulation yields a denser aggregate structure than other methods at low pressure [14]. Therefore, on the basis of the recommendations of [15], the porosity of the granule ε is taken from experiments in which transverse vibration of the liquid above the granular bed is excited.

The porosity varies in the range 0.38-0.42 for the class of particles employed. Using data on the dependence of the coordination number N on the bed porosity for ordered structures [16], ε = 0.4 corresponds to N = 8, and the following relation between β and the bed

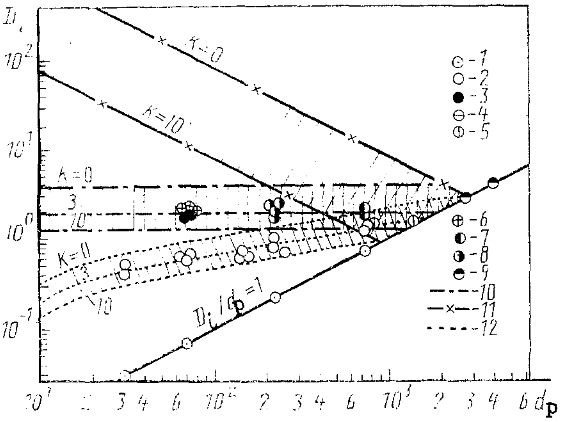

Fig. 2. Dependence of the granule diameter in a fluidized bed on the initial particle size: 1, 9) D_1; 2, 3) D_2, D_3; 4) data of [7]; 5) [5]; 6) [4]; 7) [8]; 8) [6]; 10, 11, 12) calculation by Eqs. (12), (13), and (11), respectively; 1-3, 9) f = 20 Hz, K = 3.2, U = 4%, $h/d_p = 0.05$; 4-8) f = 25-200 Hz, ρ_p = 2000-8000 kg/m³; K ≤ 80; 1-3) corundum; 9) glass spheres; d_p, μm; D_i, mm.

moisture content may be proposed

$$u_i = \frac{1}{1 + \dfrac{\rho_p}{6\rho_{li}(I + h/d_p \sin^2\beta)}}, \tag{8}$$

where

$$I = (1 - \cos\beta)\left[\sin^2\beta - (1 - \cos\beta)\left(1 - \frac{1 - \cos\beta}{3}\right)\right], \tag{9}$$

ρ_{li} is the density of the liquid; h is understood to be the gap between the grains forming on account of their surface roughness and the presence of an adsorption film: $h/d_p \approx 5\cdot10^{-2}$-$10^{-3}$ in the present case [17, 18].

The granules corresponding to case A may also break down by a different mechanism when the inertial forces increase to the level of the coupling forces in the breakdown plane (case A_2)

$$F_{co} = pF_d, \tag{10}$$

where $p \approx D_{max}^2/d_p^2$ is the number of contacts between particles in the middle cross section of the aggregate.

In case B, the particles are held within the granule by the surface tension of the liquid film surrounding the granule. In this case $\beta \to 90°$, and hence $R_1 \to \infty$, and F_{ca} is negligibly small in comparison with F_{at}; then

$$F_{co} = F_{at}(D_3) = \sigma\pi D_3. \tag{11}$$

Substitution of Eqs. (2), (3), (9), and (10) into Eq. (1) gives the desired granule diameters

$$D_2 = D_3^{2/3}(\psi d_p)^{1/3}, \tag{12}$$

$$D_3 = \left(\frac{6(1 - u_i)}{\rho_g g(1 + K)}\sigma\right)^{1/2}, \tag{13}$$

$$D_{max} = D_3^2 \psi / d_p, \tag{14}$$

where $\psi = F_d/(\pi \sigma d_p)$ is the dimensionless coupling force of the grains and varies from 0 to 1.

Comparison of experimental data with calculation reveals good correlation (Figs. 1b and 2). As assumed, the region of granule existence is bounded by the converging curves $D_i/d_p = 1$ and $D_i = D_3$; beyond the limits of this region, no aggregates are formed (point 9 in Fig. 2 with $d_p \gtrsim 3$ mm) or else they are unstable (the region between the family of curves $D_i = D_3$ and $D_i = D_{max}$). According to the observations of [19], the wet filler passes to a fluidized state accompanied by circulational motion when

$$L \geqslant D_{max}, \tag{15}$$

where L is the characteristic bed size. Over time, the initial granule size $\sim D_{max}$ in the fluidized bed decreases to a stable level of $\sim D_2$-D_3 with the given parameters of the system. In the opposite case, the filler in the apparatus remains in an internally motionless state, becomes denser, and oscillates together with the apparatus or moves in piston fashion with respect to the apparatus.

The same expressions describe the granule size obtained in irrigation of the bed by water [4-8]. Depending on the drop size, the granule size clearly tends to D_2 (fine spray) or D_3 (coarse spray) (Fig. 2b).

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