

$$\frac{dr}{dt} = \frac{\rho_1}{\rho_g} \sqrt{\frac{RT}{2\pi}} \left[1 + \frac{1}{6} k \left(1 + 2M \frac{v_-}{u} \right) - \frac{1}{\Pi\varphi} \sqrt{\frac{T}{T_g}} \exp\left(\frac{2\sigma}{\rho_g RT_g r}\right) \right]. \quad (40)$$

An analysis of the derived relationships indicates that fluctuations of the state parameters and the accompanying relaxation phenomena affect to a high degree the initial moisture formation and determine the disperse composition of the suspended phase. It should be mentioned here that, in thermodynamic devices, especially under variable conditions, the presence of separation phenomena with strongly pronounced flow pulsation, turbulent pulsating supersonic streams, and compression and rarefaction waves leads to the development of drop moisture in spite of the fact that calculations based on the mean state parameters indicate its virtual absence.

NOTATION

n , volume concentration of molecules; R , universal gas constant; T , temperature; λ , bond energy of molecules at the interface between phases; α , velocity of sound; m , molecular mass; t , time; r , radius of a condensation nucleus; g , number of molecules in a condensation nucleus with the radius r_g ; p , vapor pressure, k , isentropic exponent for vapor; u , velocity; σ , surface tension of the condensate; v , relative velocity of phases; ρ , density; M , Mach number; Π , degree of supersaturation. Subscripts: l , vapor phase; g , disperse phase; s , equilibrium parameters on the saturation curve; l, s , vapor parameters on the saturation curve; the prime denotes pulsations; a bar on top marks averaged parameters.

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DEHYDRATION OF SOLUTIONS AND SUSPENSIONS IN A FLUIDIZED BED

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UDC 66.021.35:66.099.2

The conditions for the stability of the granulometric composition of a product for continuous operation of the granulator in the nonrecycling mode are considered. The nature of the granulation as a function of the temperature of the heat carrier is analyzed when the granulation parameters of the granules are known.

It is well known that the process of drying solutions, suspensions, and melts in a fluidized bed consists in precipitating the solid material when the dispersed media are dried on the surface of the bed granules. Depending on the physicochemical compositions of the initial solutions, the temperature conditions of the drying and other factors, an increase in the particles may be accompanied by their agglomeration and simultaneous granulation. New granulation centers may be formed, particularly due to thermal granulation of the particles.

A considerable number of publications [1-3] have been devoted to the question of the thermal granulation of granules in a fluidized bed, in which it is assumed that the main mechanisms by which granulation occurs are based on the temperature difference between the bed and the solution, and also the temperature difference between the bed and the boiling point of the solution. However, the results we have obtained in semiindustrial tests of the drying and granulation of solutions of sodium sulfate, and also on suspensions of nonphenyl coagulant in a fluidized bed [4, 5] show that this approach is unsatisfactory. These tests,

Ural Scientific-Research Chemical Institute, Sverdlovsk. Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 36, No. 6, pp. 1024-1028, June, 1979. Original article submitted August 9, 1978.

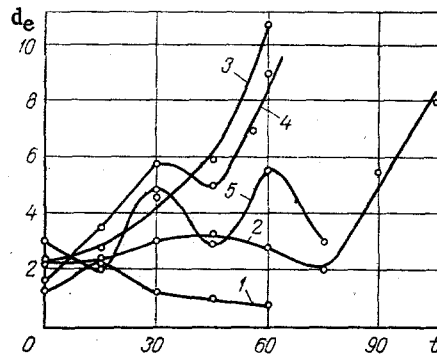


Fig. 1. Dependence of the equivalent particle size d_e on the time t for different temperatures of the heat carrier ($^{\circ}\text{C}$): 1) 300; 2) 400; 3) 500; 4) 600; 5) 700.

carried out under conditions in which a constant bed temperature was maintained while the temperature of the heat carrier applied to the fluidized bed apparatus was varied, showed that when the amount of solution was increased the granule-formation process changed qualitatively.

Experiments were carried out on a fluidized-bed apparatus of diameter 0.39 m; we used a suspension of a nonphenyl coagulant as the drying material, obtained by mixing powdered coagulant (10% Al_2O_3 and 18.5% H_2O) with water in the ratio 1:1. The suspension was added at a temperature of $75\text{--}80^{\circ}$ to the fluidized-bed apparatus, in which case the temperature of the bed T_b , the mass of the bed M , and the temperature of the solution T_s remained constant, while the temperature of the carrier T varied. The fine particles were recycled.

Figure 1 shows curves of the equivalent dimensions of the particles d_e as a function of the sampling time t for $T_b = 190^{\circ}$. In the range $300^{\circ} \leq T \leq 700^{\circ}$ the $d_e\text{--}T$ curve undergoes considerable changes. For temperatures of 500 and 600° the predominant tendency is for an increase in the particles, for $T = 300^{\circ}$ there is a reduction in the size of the particles, while for $T = 700^{\circ}$ the average dimensions of the particles varies about the mean dimensions of the pad d_0 .

A detailed analysis of the above phenomena is given in [5], but one of the drawbacks of this analysis is the fact that due to an idealization of the process the particle collision probability γ , their adhesion probability ϵ and the quantity β are assumed to be independent of the average size of the particles. Hence, for $T = T_2 = 700^{\circ}$ a self-oscillatory process is observed experimentally with $d_e(t) = d_0$ (see Fig. 1). The latter fact can be explained if we assume, as in [3], that there is a minimum size of the granules for which thermal granulation of the particles does not occur.

Thus, according to [5], when there is no external recycling, the equation describing the change in the number of particles with time has the form

$$\frac{dN}{dt} + \epsilon\gamma N^2 + \frac{1}{t_{av}} N - (\bar{m}-1)\Pi N = 0. \quad (1)$$

In deriving (1) it was implicitly assumed that the supply of heat in all cases ensures completion of the drying process. Equation (1) for the case when $\bar{m} = 2$ can be obtained from the Todes kinetic equation [1], if we multiply the latter by dv and integrate from 0 to ∞ , taking into account the fact that

$$f(v, t)|_{v=0} = f(v, t)|_{v=\infty} = 0.$$

Since in its physical meaning $1/\Pi$ is the average granulation time (the lifetime) of a particle, then, putting $(\bar{m}-1)\Pi = 1/t_g$, we can represent (1) as

$$\frac{dN}{dt} + \epsilon\gamma(t)N^2 + \left(\frac{1}{t_{av}} - \frac{1}{t_g}\right)N = 0. \quad (2)$$

The solution of Eq. (2) when $N|_{t=0} = N_0$ has the form

$$N(t) = \frac{N_0 \exp\left(-\int_0^t \beta(t) dt\right)}{1 + N_0 \int_0^t \varepsilon \gamma \exp\left(-\int_0^t \beta dt\right) dt} \quad (3)$$

Knowing $N(t)$ and taking into account the condition $\rho \bar{N} v_e = M = \text{const}$, we can obtain $v_e(t)$ and vice versa. From (3) we have for $\beta \equiv 0$

$$N(t) = \frac{N_0}{1 + N_0 \int_0^t \varepsilon \gamma dt} = \frac{N_0}{1 + N_0 \varepsilon \gamma t},$$

where $N(t)$ is a decreasing function of t and $\lim N(t) = 0$. However, it is easy to show that when $\varepsilon \gamma \neq 0$ and $\beta < 0$, $\lim N(t)$ has a finite limit different from N_0 , and at the same time, according to experimental data (Fig. 1), one can only expect stable granulation in the range of values $T = T_1 = 330^\circ$ and $T = T_2 = 700^\circ$, in which case $N(t) = N_0$ or $d_e(t) = d_0$. In view of this agglomeration can be neglected in this case (this is also confirmed by the absence of fine particles in the agglomeration product). However, this approximation cannot be made when considering processes connected with mass transfer [3].

From Eq. (3) we have for $\varepsilon \equiv 0$

$$N(t) = N_0 \exp\left(-\int_0^t \beta(t) dt\right); \quad (4)$$

$$d_e(t) = d_0 \exp\left(\frac{1}{3} \int_0^t \beta(t) dt\right). \quad (5)$$

From Eq. (5) for $\Pi = 0$ we can obtain Shakhov's equation [6] for the increase in the granules when granulation is carried out in a fluidized bed

$$d_e = d_0 \exp\left(\frac{1}{3} \frac{t}{t_g}\right), \quad (6)$$

and for $t_g = \infty$ we obtain Todes's equation for describing the processes by which size reduction occurs in a fluidized bed [1].

The equality $d_e = d_0$ when $t > 0$ only occurs when $\beta = 0$. Hence, over the temperature range we are considering the equation $t_{av} - t_g = 0$ should have at least two roots: $T = T_1$ and $T = T_2$. It is easy to understand the reasons for this result. In fact, since T_b , T_p , and $M = \text{const}$, while $T = \text{var}$ over a wide range, and $t_{av} = M/\rho Q$, both t_{av} and Q will vary over a wide range and are functions of T only.

It is easy to obtain t_{av} from the experimental data in the form of a monotonically decreasing function of T , viz.,

$$t_{av} = \frac{1}{A_1 + B_1 T},$$

where A_1 and B_1 are experimental coefficients. From physical considerations t_g must also be a decreasing (nonincreasing) function of T (Π is a nondecreasing function of T).

The qualitative picture of the arrangement of the curves of $t_{av}(T)$ and $t_g(T)$ shows that they intersect at the points T_1 and T_2 . It is characteristic that the conditions $\beta = 0$ begins in the first case when a small temperature stress acts on the particle, but for a long time, while in the second case, on the other hand, a short time and a large temperature drop.

Processing of the experimental data for the region from T_1 to T_2 shows that they obey Eq. (5) describing the unstabilized growth of the granules. The presence of an unstable process at points T_1 and T_2 , as can be seen from the analysis carried out above, is a certain idealization of the actual process. Equation (2) for $\varepsilon = 0$ gives a solution for the self-oscillatory mode, if $\beta(t)$ periodically changes sign. The achievement of a stable process in practice involves maintaining the technological parameters within narrow limits, so that irregularity of the "external" actions may be one of the reasons for the self-oscillations. An analysis of the instability of the process by which the granules increase in nonrecycling arrangements when there are "external" actions is given in [1]. Another possible source of

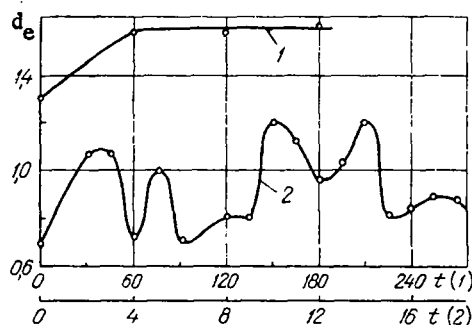


Fig. 2. Curves of d_e as a function of t (1 - t , min, 2 - t , h) for dehydration of solutions of sodium sulfate in a fluidized bed: 1) $T = 300-330^\circ$, $T_b = 110^\circ$; 2) $T = 700^\circ$, $T_b = 110^\circ$.

instability is "internal" action, connected with the dynamic thermal granulation of the granules. It is well known that the probability of thermal granulation is related directly to the critical dimensions of the granules [1,2]. Hence, if accumulation of large fractions includes the whole granulometric spectrum of particles, a self-oscillatory mode is possible (Fig. 1, curve 5). In this case initially all the particles increase to a certain size, and then an avalanche-type granulation occurs, encompassing all the particles. Such a situation, or one close to it, is possible when there is a very narrow spectrum of times during which the particles remain in the bed, i.e., for increased productivities with respect to the solid material. Taking into account the high accuracy with which the technological parameters of the process are maintained, in particular, the temperature mode, the self-oscillatory mode observed may be due to "internal" actions.

The self-oscillatory nature of the curves of d_e as a function of t at high productivities was also noticed by us in the granulation of solutions of sodium sulfate in a fluidized bed. Characteristic curves are shown in Fig. 2, where the curve of d_e against t is given for two values of T . For $T = 300-330^\circ$ the process is practically stable, while for $T = 700^\circ$ an oscillatory mode is observed. The nature of curve 1 in Fig. 2 is obviously connected with the continuous formation of new granulation centers, since the amount of the fraction with $d \geq d_{cr}$ is only a certain part of the total output of granules, and their granulation occurs on a background of a continuous increase in the particles.

The mathematical model of the granulation process with thermal granulation given above provides a true qualitative picture of the process. Naturally, for a quantitative prediction additional investigations are required, directed primarily to studying the dynamics of the granulation, taking into account the physical and chemical properties of the granules, the number and volume of the fragments formed, etc. As regards the latter, the initial equation (1) enables one to seek particular solutions for any number of fragments.

NOTATION

γ , particle collision probability; ϵ , adhesion probability of the colliding particles; ρ , apparent particle density; N , total number of particles in the bed; \bar{m} , average number of fragments formed; d_0 , average size of the initial particles; d_e , equivalent size of the particles at the exit of the apparatus; d_{cr} , critical size; t , time; $t_{av} = V/Q$, average time the particles remain in the bed; t_g , average lifetime of the particle; Π , total probability of particle granulation per unit time; v , particle volume; T , temperature of the heat carrier; T_b , temperature in the boiling layer; M , mass of the bed; Q , volume flow rate of the solid material; V , volume of the bed; and $\beta = (1/t_{av} - 1/t_g)$.

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INFLUENCE OF VIBRATIONS OF NON-NEWTONIAN FLUID FLOW

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UDC 532.5:532.135

The influence of vibrations on the exit flow of non-Newtonian power-law fluids from a vessel through capillaries of various diameters is investigated. It is found that the superposition of vibrations can either decrease or increase the time to empty the vessel.

The laminar pulsating motion of non-Newtonian power-law fluids in tubes has been investigated earlier [1,2]. It was found that the superposition of pressure pulsations on a steady non-Newtonian fluid flow in tubes can have the effect of increasing the average flow rate over one oscillatory period for pseudoplastic fluids and decreasing it for dilatant fluids.

We have conducted experimental investigations on an apparatus consisting of a cylindrical glass vessel, at the bottom of which was fused in a glass tube with a length of 15 cm and a diameter varying from 1 to 5 mm. The apparatus was thermostatically regulated and placed on a shake table. Vibrations were generated electromechanically in the frequency range from 0 to 70 Hz with an amplitude of 1 mm. The time for a specified quantity of fluid to flow out through capillaries of various diameters at a uniform temperature of 25°C was determined.

The experimental liquids were solutions of polyacrylamide (PAA) of various concentrations with the addition of 1% surfactant of the type DS-RAS, as well as petroleum. The rheological curves for flow of the investigated liquids show that they can be regarded as pseudoplastic non-Newtonian fluids.

The experimental results are shown in Figs. 1a-c, which give the exit time of a specified quantity of liquid from the vessel through capillaries of various diameters as a function of the vibration frequency. The concentrations of the PAA solution and the capillary diameters are indicated in the figure caption.

The results indicate that the superposition of vibrations on the exit-flow of the investigated liquids is effective at low vibration frequencies (around 10 Hz) and for flow through small-diameter capillaries. In the flow of PAA solutions with concentrations of 1% or higher through capillaries with diameters of 3 mm or more, the vibrations have scarcely any influence on the flow process. The effect of the vibrations vanishes for the investigated petroleum when the capillary diameter is increased above 4 mm.

We now analyze theoretically the flow of non-Newtonian fluids obeying a rheological power law from a vessel through vertical tube fused into its bottom.

The equation of motion of the fluid in the tube has the form

$$\rho \frac{\partial v}{\partial t} = - \frac{\partial p}{\partial z} - \frac{1}{r} \{ r \tau_{rz} \} + \rho g, \quad (1)$$

$$\tau_{rz} = k \left(- \frac{\partial v}{\partial r} \right) \left| \frac{\partial v}{\partial r} \right|^{n-1}. \quad (2)$$

At the initial time $t = 0$, the flow velocity of the fluid is equal to zero. For $t > 0$,

$$- \frac{\partial p}{\partial z} = \frac{\rho g h(t)}{l}, \quad (3)$$

where $h(t)$ is the level of the fluid in the vessel and l is the length of the tube. Substituting relations (2) and (3) into Eq. (1), we obtain

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