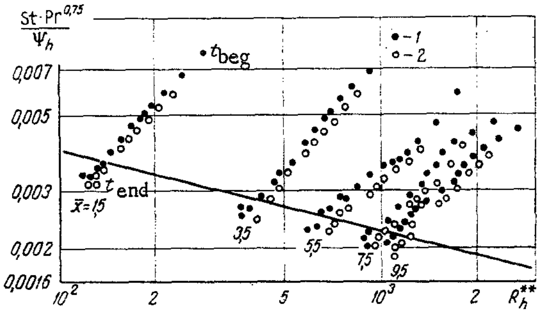

Fig. 3

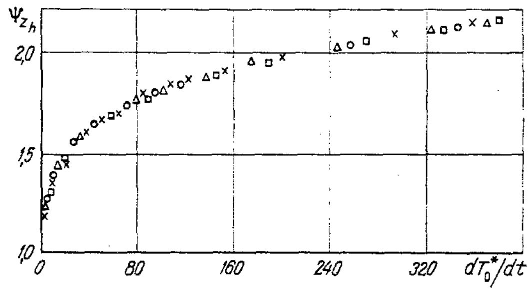

Fig. 4

Fig. 3. Dimensionless heat-transfer coefficient as a function of R_h^{**}. Points, experiment: 1) $\rho_{01}w_{01} = 26.9\ g/cm^2 \cdot sec$; 2) $\rho_{01}w_{01} = 30.25\ g/cm^2 \cdot sec$; lines, calculation based on the equation $St = 0.0128/R_h^{**0.25}Pr^{0.75}$.

Fig. 4. Influence of dT_0^*/dt (deg/sec) on the relative heat-transfer coefficient.

NOTATION

Bi, Biot number; D, diameter; Pr, Prandtl number; R_h^{**}, characteristic Reynolds number of the thermal boundary layer; St, Stanton number; T_0^*, stagnation temperature of the main gas flow; T_w, wall temperature; t, time; x, longitudinal coordinate; Δ_w, thickness of wall material; ψ_h, enthalpy factor; Ψ_h, parameter representing deviation from isothermal conditions; Ψ_{Z_h}, relative heat-transfer coefficient, allowing for the effect of thermal transience due to the changes in the temperature of the main gas flow; Ψ_Σ, relative change in the Stanton number for R_h^{**} = idem.

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MECHANICS OF JET FLOWS IN GRANULAR LAYERS. EVOLUTION OF SINGLE JETS AND THE NUCLEATION MECHANISM

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UDC 532.546

A physical analysis of the dynamics of jet development and the formation of a gas bubble in a high fluidized bed is presented.

Fluidized or fixed granular layers with jet delivery of excess liquefier are so widespread that their applied value needs no recommendations. Let us note just two main types of jet flows which differ in principle. First, the whole gas can be supplied as a jet in an initially fixed layer with the possible build-up of a fluidized state, starting from some level above the gas-distributor grating. Secondly, jets can be introduced into an already fluidized or almost fluidized layer to improve the quality of the fluidization or to intensify the exchange processes. In both cases, both the characteristics of the individual jets and their interaction, which mainly govern the layer structure observed, are of primary value.

The physical picture of jet development in a fluidized bed was described phenomenologically in [1-3], for instance. In particular, stationary and self-oscillating escape modes and an intermediate mode of local spouting

Institute of the Problems of Mechanics, Academy of Sciences of the USSR. Moscow Institute of Chemical Machine Construction. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 30, No. 5, pp. 825-833, May, 1976. Original article submitted May 27, 1975.

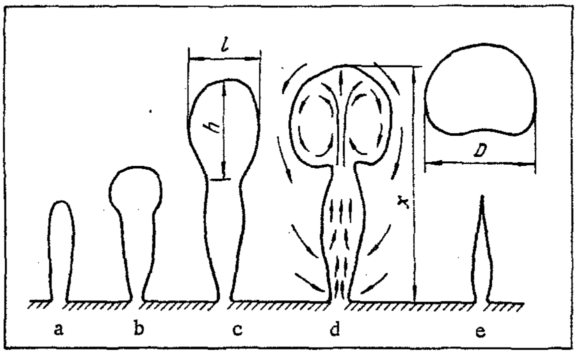

Fig. 1. Successive phases of jet development with nucleation. The arrows (d) show the direction of particle motion in the cavern and in the dense phase of the fluidized bed.

were extracted [2, 4]. However, the theory of jet flows which would permit foreseeing the effect of initial escape conditions and bed parameters on the bed structure in advance, perceiving their application in the organization of different technological processes, is substantially nonexistent (the exception is just a quantitative investigation of the limit stationary mode of the escape of jets piercing the bed in [4]). A representative model of periodic nucleation during the collapse of gas flares is also missing: there are just single experimental [5] or semiempirical [6, 7] investigations based mainly on the application of results obtained for the escape of a gas into an inviscid fluid [8, 9].

So unsatisfactory a situation is due primarily to the multiformity of the physical factors which are essential to the development of a disperse jet, as well as to the absence of a clear understanding and the difficulties of modeling each of them in practice. Under such conditions a formulation of a qualitative physical model of the process which would result in clarification of the main reasons responsible for the realization of the phenomena observed and would permit clarification of the desirable directions for further study is completely necessary in order to construct a quantitative theory of engineering design methods. To this end, known test facts were analyzed carefully, and a complex of additional experimental investigations of the escape of plane, axisymmetric, and semilimited jets in fixed and fluidized beds was also carried out in a broad range of variation of the bed parameters and escape conditions. Granular materials of different density in dispersion were used; plane holes and nozzles of different size and shape with an independent gas delivery, as well as gas distributor gratings of different kinds and geometries, were used as the sources of the jets or collections of jets. The tests were conducted on apparatuses with bulk and flat beds which are a certain development of the apparatus described in [10]. These apparatuses were equipped with a standard control-measuring device; moreover, moving pictures were taken, whose rates were selected individually in each case.

The volume of experimental material obtained turned out to be quite huge and diverse. Only results referring to the dynamics of single jet development and to nucleation in a preliminarily fluidized bed, as well as quantitative deductions on their analysis which are essential to the comprehension of the processes originating, are presented in this paper in very compressed form.

Observations of jet evolution in a high layer confirm the phenomenological picture described in [2, 3] and can be summarized briefly as follows. An elongated cavern, which increases in size until achieving a height close to the maximum height of the flare x in a time approximately equal to or somewhat exceeding half the total time of nucleation (Fig. 1), is formed from the beginning of the escape from the nozzle or hole. Up to this time the cavern shape is quite regular and initially almost conical in the lower part and ellipsoidal in the upper part of the flare (Fig. 1a). Later, broadening of the head part of the growing flare starts and "necks" separating this part from the lower conelike part of the cavern develop (Fig. 1b). As the flare grows, the neck is shifted upward and, finally, when the flare reaches a height close to x, turns out to be at a distance above the nozzle exit equal approximately to (0.55–0.60)x. The process of lateral expansion of the upper part of the flare does not terminate here, but continues until the horizontal dimension of the upper part l approximately agrees with the vertical dimension $h \approx (0.40-0.45)x$ so that the shape of this part becomes almost spherical. Afterwards, a rapid "collapse" of the neck occurs with the formation of a bubble which starts to rise independently in the bed. During the collapse, the part of the gas being contained in the lower part of the cavern rapidly penetrates into the bubble, and the flare above the hole is reduced strongly in size, where its shape at this time turns out to be random to a significant extent. The remaining flare is later developed according to the previous scheme with a new bubble forming, etc., i.e., a unique, self-oscillating process occurs which is especially regular in the case when the volume of the remaining flare and the jet escape velocity are not too high. The regularity is spoiled somewhat at high escape velocities because of the possible penetration of the gas from the new developing flare into the bubble being formed in the preceding cycle, i.e., because of partial "make-up" of this bubble by the gas from the new jet. Consequently, some chaotic spreading of the volumes of successively forming bubbles relative to the mean value is observed in this case.

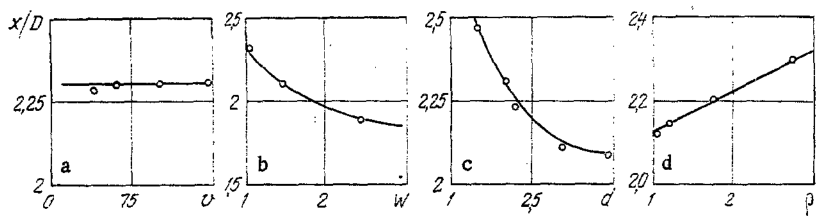

Fig. 2. Dependence of the ratio x / D on different parameters for semilimited jets with a = 4 mm. The experimental points in (d) correspond (in order of increasing density) to polystyrene, aluminosilicate catalyst, granulated nitrogen–phosphorus–potassium fertilizer, and glass balls; all the rest correspond to the aluminosilicate catalyst; U = 98 m / sec (except a); W = 1 (except b); d = 2.24 mm (except c); v, m / sec; d, mm; ρ, g / cm^3.

It is clear that penetration of the developing flare into the bubble is possible if the initial rate of bubble ascent (which can be estimated on the basis of the results in [11, 12]) is commensurate with or less than the rate of advance of the upper cavern boundary in the first phase of the self-oscillation cycle. Then the layer between the bubble and the cavern is thin and its hydraulic drag to the filtering gas stream is low, i.e., conditions are produced for the preferable upward eruption of the gas. In particular, for a constant gas discharge into the jet G = US, i.e., for constant volume and velocity of the bubbled being formed, the make-up of the bubbles should be facilitated with diminution in the area S of the hole, i.e., as the initial jet velocity U increases, as is actually observed.

As in the case of stationary jets in a low fluidized bed [4], the lower part of the jet under consideration exerts a draining effect on the adjacent bed volumes and there is considerable gas injection into this part of the jet. Injection ceases near the contraction of the flare, and the sign of the effect under consideration is reversed; gas ejection from the jet into the dense phase of the bed occurs in the region above the contraction. Simple reasoning analogous to that in [4] shows that the distribution of the injected gas stream over the height of the lower part of the jet can be estimated approximately by using relationships of the same kind as in [4] if the height of the location of the flare contraction over the grating is taken as the effective height of the low layer in these latter. Indeed, the gas stream distribution in the dense phase of the bed around the cavern is described in a first approximation from the solution of the same filtration problem as in [4], under the conditions of constant gas pressure in the cavern and stream continuity on its moving boundary. Such a problem possesses a high degree of self-similarity and is actually characterized by a single free parameter – the pressure in the cavern, which evidently agrees with the gas pressure in the dense phase far from the cavern at the level of the contraction location. The self-similarity of the problem immediately results in a deduction about the similarity of the cavern shapes being formed under different conditions and, in particular, about the independence of the ratio x / h ~ x / D from the jet escape velocity U (Fig. 2a). The dependence of this ratio on the fluidization number W, for instance (see Fig. 2b), also becomes conceivable, since an increase in the porosity of the dense phase contributes to easier gas penetration from the jet into this phase and, as a result, to an appropriate reduction in the level of the contraction above the grating.

Particle injection into its lower part is also observed during jet development, where the density of the particle stream reaches a quite definite maximum directly at the plane of the hole or at the nozzle exit. Qualitatively, this is in complete agreement with the model in [4]. However, in quantitative respects, the preliminary estimates from [4], obtained on the basis of examining the dense phase of the bed near the cavern in an ideal fluid approximation, turn out to be exaggerated substantially, at least in cases when the fluidization number does not greatly exceed one.*

*This is apparently related to the inapplicability of the ideal fluid model to sections of the dense phase depleted of gas because of its outflow into the jet. If the fluidization number is not too large, then such injection is completely adequate for the local gas velocity in the sections mentioned to become less than the initial fluidization velocity. Consequently, the motion of the dispersed phase near the cavern will be more reminiscent of the slipping of layers of friable material over surfaces governed by the effective local values of the angle of repose than the motion of a truly fluidized system, so that neglecting the tangential stresses (the effective "viscosity" of the disperse phase) becomes illegitimate. Such slipping of the layers is traced especially clearly in examining moving pictures of jet flows. The authors are grateful to Yu. I. Makarov for discussing this viewpoint, which is completely confirmed by the test facts.

The incoming particles are caught up by the gas stream and carried to the upper part of the cavern. The ascending particle motion is hence irrotational and their distribution over the jet section depends mainly on the particle inertia and the section area. Thus, fine particles coming into a comparatively broad jet are carried upward primarily in the layer adjoining the cavern walls. It is clear that a diminution in the particle diameter will result in attenuation of the gas ejection into the dense phase from the jet flare and, therefore, also in a resultant rise in the level of the contraction. This is confirmed by the experimental results (Fig. 2c).

On the other hand, sufficiently coarse particles penetrate into the central region of the jet (certainly if the latter is not too broad) and form a "braid" localized along the jet axis or plane of symmetry. Clearly, the jet momentum losses will be higher, but the pressure in the cavern will be lower, the heavier the particles of the braid being accelerated, i.e., the level of flare contraction rises with the increase in density of the particle material, and the parameter x/D grows correspondingly (see Fig. 2d). As in [4], approximate conservation of the shape of the lower part of the cavern during jet development indicates that a dynamic balance occurs between the number of particles approaching its surface because of slipping of the dense phase layers and the number of particles caught up by the jets.

The particles carried off by the gas into the domain above the contraction continue their ascending motion until they emerge on the cavern boundary. Despite some horizontal scattering of the cluster of particles, their main mass is incident, namely, in the upper part of the dome-shaped cavern surface and retained there partially. The remaining particles are discarded to the side after colliding with the surface and slip downward along the surface under the effect of gravity. (The hydraulic force acting on the particle influences such slip quite weakly. Indeed, there is just a normal component of this force which squeezes the particle to the surface and prevents it from standing off. The tangential component of the force is almost zero, since the gas stream being ejected through this surface is directed practically normally to it.) Near the contraction, the slipping particles are discarded by inertia into the core of the ascending gas jet and are again entrained towards the dome, where they can either be captured by the dense phase or again involved in a slipping descent. Therefore, intensive particle circulation* originates in the domain above the contraction, with a descending motion in a comparatively narrow zone near the surface and with an ascending motion in the jet core. The direction of particle motion in the cavern and in the dense phase is provisionally shown by arrows in Fig. 1.

The hydraulic forces acting on particles at the walls of the upper part of the cavern from the ejected gas stream contribute to driving the dispersed phase back from the center of the jet and to a corresponding broadening of this part of the cavern. Hence, in contrast to the situation in the lower part where there are conditions needed for the buildup of a dynamic balance of the particles coming into the jet and supplied to its surface because of the motion in the dense phase, such a balance can hold in the domain above the contraction only near the upper part of the dome to which the particles from the jet come in without hindrance. Particles from the jet are not delivered to the side walls of the dome in practice so that the balance of particles is spoiled here and the lateral expansion of the upper part of the flare which is observed has a natural explanation.

The gas velocity at the dome apex is evidently equal to Q/h^2 in order of magnitude, where Q is some unknown effective value of the gas stream in the jet with its injection and ejection taken into account and which should be close to the particle soaring velocity V. If this velocity were to be less than V, then sprinkling of the particles would have been observed with a downward displacement of the visible dome boundary; if it were considerably greater than V, then a further dome development would have occurred, i.e., upward displacement of its front boundary. Therefore, the ordering equality

$$h \sim (Q/V)^{1/2} \tag{1}$$

is the necessary condition for stable location of the cavern upper boundary. Since the soaring velocity grows with the increase in the particle size and density, but the stream Q should depend quite weakly on them, then the dependences on the parameters mentioned (Fig. 3c and d) observed for the diameter of the bubbles being formed become conceivable from (1), i.e., actually the quantity h.

*It should be mentioned that such a circulation greatly recalls the vortex motion observed in gas jet injection into a fixed granular layer with the formation of a stable cavern. This is not astonishing, since the circulation is caused by the very same physical reasons in both cases. The single distinction is that the circulation domain (as well as the cavern itself) is bounded externally by fixed granular material during injection in a fixed layer, while it is bounded by downward slipping material of the dispersed phase during blowing in a fluidized bed, so that there is visually a continuous transition from particles taking part in such circulations within the cavern to particles moving in the composition of the dispersed phase for high fluidization numbers, and the concept of a clear cavern boundary becomes somewhat provisional.

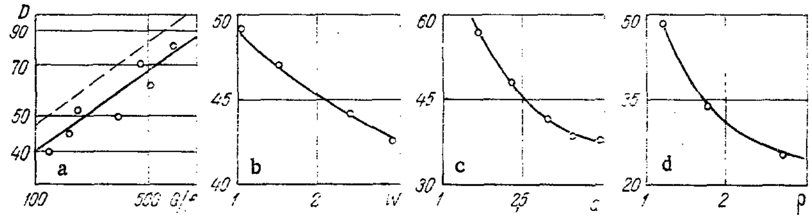

Fig. 3. Dependence of the bubble diameter D on different parameters. Conditions for conducting the tests are the same as in Fig. 2: a) the solid curve follows from (5) for k = 0.37, and the dashes are for k = 0.53; G / f, cm^3; ρ, g / cm^3.

The gas velocity in the central part of the cavern above the contraction is determined by the degree of flare expansion after the contraction, i.e., it can be written as Q/l^2. In the initial broadening phase, when $l < h$, this velocity exceeds V and the particles in the jet core actually move upward. However, for $l \sim h$ the velocity mentioned is comparable to V and then becomes somewhat less than V. Consequently, the rising particles, or part of them in any case, are decelerated as they rise. Some of them lose velocity before reaching the apex of the dome and drop downward to emerge in a domain near the contraction where they are again caught up by the jet. Therefore, accumulation should occur near the contraction of particles both brought from the bottom by the jet and dropping from the top. The latter is equivalent to the known effect of "flooding," observable quite often in dispersed streams, and should result in the inevitable filling of the flare contraction by the particles, i.e., the formation of dikes separating the upper and lower parts of the cavern, and to the beginning of the existence of the upper part as an independent formation (bubble). The reasoning presented is in good agreement with observations; it also becomes understandable why bubble separation occurs only when the horizontal cavern dimension l reaches values close to h. Any factor facilitating gas ejection in the dense phase will result in a relative diminution of the gas velocity in the jet and, as a result, in the diminution in the diameter $D \sim h \sim l$ of the bubbles being formed (and conversely). Shown as an illustration in Fig. 3b is the dependence of D on the fluidization number W: the mean porosity and hydraulic drag of the dense phase decrease with the growth of W, and the bubble size diminishes correspondingly.

To estimate the volume of the bubbles, let us consider the blowing of a jet into a high fluidized bed ($x/H \ll 1$). The rate of expansion of the upper part of the cavern (the velocity of the motion of its vertical walls in the horizontal direction) is proportional to $(gh)^{1/2}$ (see [4]) so that the characteristic time of expansion is

$$\tau \sim h(gh)^{-1/2} = (h/g)^{1/2}. \tag{2}$$

The volume of gas coming in from the jet to this bed during this time is τG, i.e.,

$$D^3 \sim h^3 \sim G(h/g)^{1/2}. \tag{3}$$

Hence, there follows

$$D \sim h \sim G^{2/5} g^{-1/5}, \quad v \sim G^{6/5} g^{-3/5}. \tag{4}$$

Under the assumption that the volume of bubbles being formed per unit time is proportional to the gas discharge in the jet [8, 9], we can write

$$v = kG/f, \tag{5}$$

where k is a coefficient less than one and takes account of partial gas ejection into the dense phase of the bed. We have the following estimate for the frequency of nucleation f from (4) and (5):

$$f \sim kG^{-1/5} g^{3/5}. \tag{6}$$

Formulas (4)-(6) have the same form for k = 1 as those obtained in [8] in the analysis of gas escape into an ideal fluid, and they are verified by experiment (including [6, 7]) to the same degree as the formulas from [8]. However, in contrast to these latter, they take account of the possibility of partial gas efflux from the growing cavern through the dense phase of the bed (the importance of such an efflux was apparently noted first in [9]). It follows from general physical considerations and from an analysis of the test data that k depends quite weakly on the bed parameters and the jet escape mode; however, a quantitative estimate of k is difficult in connection with the absence of a more complete theory of bubble formation and can only be made on the basis of an experimental investigation. The results in Fig. 3a which refer to different beds and flow modes verify the assumption about the constancy of k. According to these results $k \approx 0.37$, which is somewhat below the value $k \approx 0.53$ presented in [9].

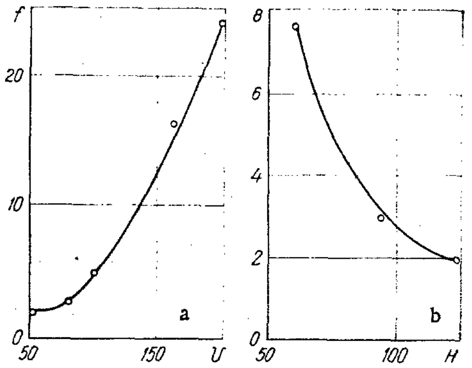

Fig. 4. Dependences of the nucleation frequency f on the velocity of jet escape U (a) and the bed height of an aluminosilicate catalyst H (b) for a semibounded jet in the local spouting mode: a = 4 mm; d = 2.24 mm; W = 1; a) H = 125 mm; b) U = 52.2 m/sec; f, Hz; v, m/sec; H, mm.

The reasoning above refers to spatial (or semibounded) jets; for plane jets we obtain completely analogously in place of (4) and (6)

$$D \sim G^{2/3} g^{-1/3} \delta^{-2/3}, \quad v \sim G^{4/3} g^{-2/3} \delta^{-1/3}, \quad f \sim kG^{-1/3} g^{2/3} \delta^{1/3}. \tag{7}$$

Let us note that the bed was assumed high everywhere above so that the inequality $x/H \ll 1$ was satisfied. The dense phase layer separating the cavern from the space above the layer becomes thinner with the diminution in bed height, and conditions appear which are conducive to preferable gas ejection through, namely, the upper part of the cavern dome (the situation here is analogous to that discussed above in analyzing the possibilities of the flare erupting into a bubble being formed earlier). Clearly, this should result in an increase in the cavern height x and a drop in pressure therein as compared with the analogous cavern in a high bed. Consequently, as the ratio x/H increases the domain of flare contraction shifts upward, the bubble volume decreases, and the frequency of their formation grows correspondingly. Presented in Fig. 4 are the characteristic dependences of f on the jet velocity U and the bed height H obtained for jets escaping into modes similar to the local spouting mode ($x/H \leqslant 1$) and completely confirming the reasoning expressed. These dependences are of interest in connection with the definite advantages of fluidized beds with jets escaping into the local spouting mode in the organization of certain technological exchange processes.

NOTATION

a, hole or nozzle diameter; D, bubble diameter; d, mean particle diameter; f, nucleation frequency; G, total gas discharge into the jet; g, acceleration of gravity; H, working height of the bed; h, height of the upper part of the jet cavern; k, coefficient in (5); l, maximum diameter of the upper part of the cavern; Q, effective discharge in (1); S, area of the nozzle or hole section; U, initial jet velocity; V, soaring velocity of the particles; v, bubble volume; W, fluidization number; x, maximum cavern height; δ, plane layer thickness; ρ, density of the filled bed.

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