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MECHANICS OF JET FLOWS IN GRANULAR LAYERS. COALESCENCE OF BUBBLES IN CONSTRAINED FLOW CONDITIONS

Yu. A. Buevich and G. A. Minaev

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The coalescence of bubbles forming during the injection of a system of parallel jets into a high fluidized layer is investigated. The effect of the parameters of perforated gas-distributor arrays on the formation of the layer structure is briefly discussed.

A system of parallel jets is very often used for fluidization of granular layers and also for improving the characteristics of layers fluidized by an independent homogeneous flow. In both cases the characteristics of these jets have a marked effect on the formation of the layer structure as well as on the intensity of the processes of heat and mass transfer realized in the layer. From the point of view of applications the main interest lies in the interaction of jets and the bubbles forming in them and in their dependence on the characteristics of the layer itself as well as on the initial parameters of the jets (shape and size of nozzles or apertures, velocity, the step between adjacent apertures, and so forth). It is just this interaction that primarily determines the nature of gas distribution and the required structure of the fluidized layer so that its investigation is entirely necessary for developing methods of layer structure control and engineering techniques of its computation, as well as for the construction of gas-distributor units.

In spite of the obvious practical significance of this problem, its meaningful investigation is still in a rudimentary stage (for example, see [1]). There are only isolated empirical or purely engineering investigations of particular problems encountered in the construction or operation of certain equipment. Theoretically, constrained motions in a fluidized layer have been investigated only in connection with the restricting effect of the equipment walls on the distribution of gas flows around a solitary bubble [2], with the interaction of two closely spaced bubbles in an infinite layer [3], and with the mutual effect of two stationary adjacent plane jets on gas injection and the particles in each of these jets [4]. Below, the results of experiments on the investigation of the interaction of parallel jets in a high layer and on the determination of the height of primary coalescence of bubbles as a function of the physical and regime parameters are presented and discussed.

A system of two semiinfinite vertical jets flowing out into a fluidized layer of particles of polystyril, nitroammophosph (a nitrogen—ammonium—phosphorus fertilizer), aluminosilicate catalyzer, and sand of different granulometric composition was taken as the initial objects for investigation. In most experiments the

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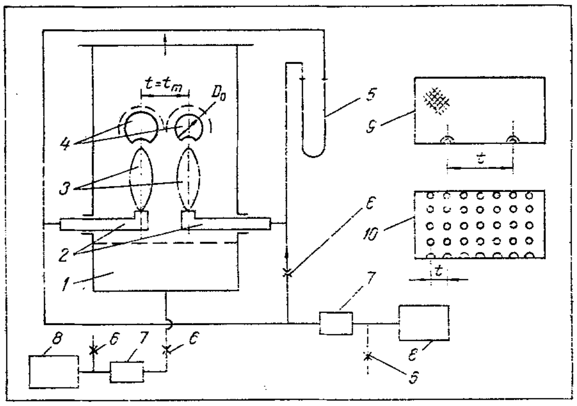

Fig. 1. A schematic diagram of the experimental setup: 1) equipment; 2) nozzles; 3) jet flares; 4) gas bubbles; 5) manometer; 6) shut-off device; 7) flowmeter; 8) heater; 9) plan of the equipment during the operation with two nozzles; 10) plan of the equipment during operation with a set of visual jets.

fluidization number was close to unity. A schematic diagram of the experimental setup with equipment of rectangular cross section (area of the array 0.025 m^2) is shown in Fig. 1. The equipment was provided with the necessary measuring and control instrumentation and also with a system of separate supply of air under the array and to the nozzles. Semiinfinite nozzles of 6-mm diameter were placed directly at the transparent wall of the equipment with the plane face against the wall; this permitted visual observations and motion pictures of the flow process (with frequency from 32 to 3000 frames/sec). The construction of the equipment had provision for measuring the steps between nozzles; the uniformity of gas distribution between the nozzles was regulated by a differential manometer.

The development of two adequately spaced jets (at distances exceeding twice the flare height x of a single jet) in a fluidized layer occurs in the same way as the development of single jets investigated in [5]. The overall intensifying effect of intense stationary jets exiting almost to the surface of the layer on the internal hydrodynamics of the layer extends to a distance from their axes that approximately coincides with x. However, intense circulation of particles induced by each jet extends to a distance of about x/2. In particular, for the step between jets equal to x or smaller the nature of motion of particles in the interflare zone is determined exclusively by the outflowing jets. These conclusions are in complete agreement with the analysis in [4].

These effects tend to decrease with the decreasing strength of the jets, i.e., in transition to the self-oscillatory outflow regime. In this case, the horizontal extension of the zone of influence of the jets on the surrounding solid phase is no longer determined by the total height of the flare but by the height of its constriction above the end of the nozzle, which is about (0.55-0.60)x [5]. The intensifying effect of the jets in the vertical direction extends to a distance of the order of the coordinate of the zone of primary coalescence of the bubbles.

On decreasing the distance between the jets, the intensity of the motion of particles in the interflare zone as a whole increases and for a small fluidization number the size of the stagnant zone, which forms between the jets as a result of depletion of the solid phase by the gas due to its predominant injection into the jet flares, decreases. With further decrease of the distance between the jets the jets begin to merge.

The minimum distance between the centers of the nozzles or apertures, at which the merger of jets or the coalescence of the forming bubbles does not begin right up to attaining a certain level above the end of the nozzles, is of special interest both from purely scientific and applied points of view. This distance was determined as a function of the conditions of jet outflow and the layer parameters. Experimental data show that this distance is determined by the condition of contact of the regions of close circulation of particles around the bubbles generated by the jets. Thus, the different parameters (fluidization number, flow rate of gas into the jets, the density and particle size, and so forth) affect this distance to the same extent as they affect the size of the forming bubbles and rate of their growth as they rise in the layer.

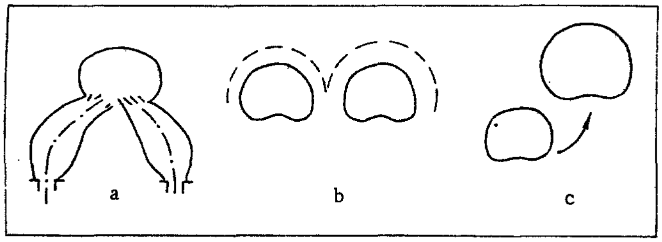

Fig. 2. Mechanism of coalescence of jets and bubbles: a) coalescence of jets with generation of a single bubble; b) radial coalescence of identical bubbles; c) capture of a small bubble in the wake zone of a large bubble.

One can distinguish the three basic mechanisms of coalescence of jets or bubbles illustrated in Fig. 2. First, there is a random merger of the jets themselves with the formation of a single bubble (Fig. 2a). This mechanism is especially characteristic for closely spaced jets for $t \leqslant D_0$ and also for jets in the stationary regime or regime of local gushing. Secondly, there is the radial coalescence of synchronously forming bubbles (Fig. 2b); thirdly, there is the coalescence caused by the capture of a smaller bubble in the wake zone of a large bubble observed in the case of appreciable asynchronous flow of adjacent jets (Fig. 2c). These mechanisms operate for jets flowing out into a high fluidized layer in the self-oscillatory regime if the step between the jets satisfies the inequality $t > kD_0$, where k is a coefficient which represents the ratio of the diameter of circulation zone to diameter D_0 of the generated bubble. There are many theoretical and empirical estimates of k in the literature (a review is given in [6]); for engineering purposes one can take $k \approx 1.2$-1.5. We note that the condition of absence of coalescence caused by the merger of identical bubbles is more rigid than the condition of absence of coalescence during asynchronous development of adjacent jets.

The typical nature of the minimum step t_m between jets, at which the coalescence in a given layer is generally absent, is shown in Fig. 3 as a function of the layer height. For small values of H, t_m is almost constant. This indicates that in this case the coalescence occurs due to direct contact of the jet flares near the upper boundary of the layer at the time of the generation of the bubbles. On increasing H, t_m increases. This means that the bubbles forming over adjacent nozzles do not coalesce at the moment of generation but begin to rise in the layer as independent formations. As they rise in the layer, their size grows (the growth of moving bubbles has been investigated in [7,8]) and, finally, comes the instant when their outer shells bounding the zone of close circulation of particles touch each other, which also denotes the start of coalescence of the bubbles. For a layer of a given height H the step t_m is determined as that distance between the axis of the nozzles at which the coalescence begins exactly at the upper boundary of the layer, i.e., at a height H above the array (in this case H plays the role of the height of the zone of primary coalescence). We note that here we are considering coalescence of identical bubbles (see Fig. 2b); the coalescence of bubbles of different sizes occurs earlier, other conditions remaining unchanged, i.e., at higher distances above the array.

The dependence $t_m(H)$ in the high layer can be estimated making use of the new theory of motion of gas bubbles in a fluidized layer presented in [9,10]. For large values of H, when the path traveled by the bubbles before coalescence is large compared to the distance at which the stationary characteristics of their motions are established, one can neglect the deviations of the initial velocity of the bubbles from their stationary value [11]. Then from [9,10] we get the equation for the change of volume v of the bubble with the height of rise:

$$\frac{dv}{dH} = C\sqrt{v}, \qquad (1)$$

where the coefficient C depends on the physical parameters of the phases of the layer and rate of fluidization; in particular, it increases with the density and the size of the particles. The equation for the equivalent diameter D of the bubble analogous to Eq. (1) is of the form

$$\frac{dD}{dH} = \frac{C'}{\sqrt{D}}, \quad C' = \left(\frac{2}{3\pi}\right)^{1/2} C. \qquad (2)$$

The solution of this equation for the initial condition $D = D_0$ for $H = H_0$, where H_0 is the coordinate of the center of the generated bubble, is

$$D^{3/2} - D_0^{3/2} = 3/2\, C' (H - H_0). \qquad (3)$$

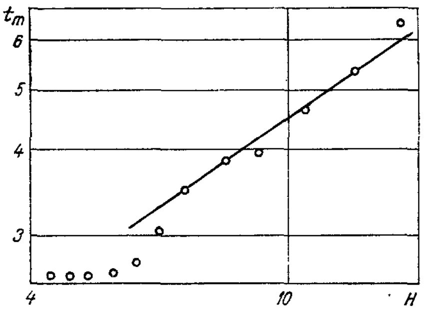

Fig. 3

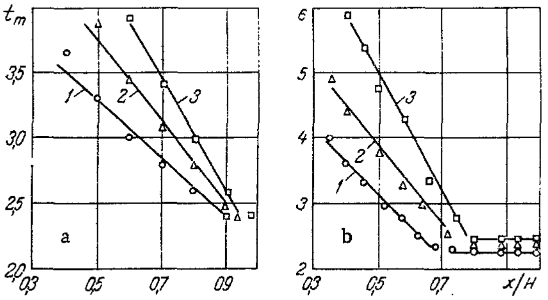

Fig. 4

Fig. 3. The dependence of minimum step between jets on the height of primary coalescence for a layer of nitroammophosph: $d = 3.24$ mm; $U = 47.2$ m/sec; the continuous line corresponds to Eq. (4).

Fig. 4. Dependence of the minimum step t_m on the parametric criterion x/H: a) layer of aluminosilicate catalyzer for $d = 2.83$ mm [1) $U = 26.4$, 2) 39.5, and 3) 52.7 m/sec]; b) layer of nitroammophosph for $U = 30$ m/sec [1) $d = 1.41$, 2) 2.24, and 3) 3.24 mm]. t_m, cm.

For bubbles in the very high layer, the relations $D \gg D_0$ and $H \gg H_0$ hold, so that we have

$$t_m = kD \approx cH^{2/3}, \quad c = k(3C'/2)^{2/3}. \tag{4}$$

A function of form (4), giving the asymptotic form of the true function $t_m(H)$ for large values of H, is also shown in Fig. 3.

The above discussion shows that the minimum step t_m depends substantially on the relationship between the layer height and the maximum height of the jet flare. Therefore, it is advisable to investigate the dependence of t_m on the parametric criterion x/H; this dependence is illustrated in Fig. 4 for different exit velocities of the jets (a) and different particle diameters (b) for fluidized layers of particles of aluminosilicate catalyzer and nitroammophosph. The curves in Fig. 4 have kinks corresponding to a certain critical value of x/H, whose dependence on the different parameters is determined in an obvious manner by the dependence of the diameter D_0 of the generated bubble on these parameters; this dependence has been discussed in detail in [5] and, therefore, is not discussed here. For the values of x/H exceeding the critical value, the coalescence occurs due to direct contact of the jets or the circulation sheets around the bubbles at the time of generation; for small values of x/H the bubbles coalesce after traversing a certain path in the layer (comparable with curve in Fig. 3). From (4) we obtain the following asymptotic representation near the coordinate origin in Fig. 4:

$$t_m = cx^{2/3}(x/H)^{-2/3}. \tag{5}$$

Hence it is clear that the slope of the curve in Fig. 4 in the region of small values of x/H is steeper for larger hitting range of the jets x and for larger values of parameter c (i.e., for example, for larger initial exit velocity U and larger or heavier particles). The data in Fig. 4 and also other experimental results of the same type substantiate this conclusion; the expected increase of t_m with the increase of the particle density of the layer is also observed.

We note that along with formulas (4) and (5), for engineering purposes we can recommend a simple empirical relationship

$$\frac{t_m}{D_0^*} \approx \frac{1.1}{x/H}, \tag{6}$$

which has been confirmed by the experiments for $0.2 \leqslant x/H \leqslant 0.6$ with an accuracy up to 25%. In (6), D_0^* is the diameter of the bubble whose volume is equal to the maximum volume of the flare.

The physical picture of interaction jets described above is qualitatively confirmed also by analogous experiments conducted with a set of two or more plane jets flowing into a prefluidized two-dimensional granular layer. Furthermore, the characteristics of coalescence of bubbles — the estimates of the height of the zone of primary coalescence H and the step t_m between the jets required for ensuring a given value of this height — remain practically unchanged even in situations when there is a system of three-dimensional or plane jets injected into a stationary granular layer from apertures of a perforated array and leading to the transition of the layer into a fluidized state. This fact enables us to automatically use laboratory results of the type described above for direct modeling and computation of the zone of coalescence in real equipment with different construction of the gas distributor and to compare the efficiency of gas distributing arrays of different types.

This similarity of phenomena observed in a prefluidized layer and a stationary layer is entirely natural. Actually, the interaction of jets and generation of bubbles begins at a height comparable with x where the particles are in an approximately identical fluidized state in both the cases. At the same time, there are also some significant differences. First, during the blowing-in of jets into a stationary layer, stagnant zones are formed in the intermediate space between the jets, and an additional injection of the gas into the lower part of the jet flares does not occur; this must lead to a lowering of the height of the flares compared to jets in the fluidized layer. Secondly, the constrained nature of the flow slows down the injection of gas from the flares, which must cause a relative increase of the height. On the whole, as special experiments on fluidized granular layers above perforated arrays of four types showed, the difference between jets forming above the apertures of the array for fluidization of the layer and jets flowing out from apertures of the same diameter in a prefluidized layer is very small and usually lies within the experimental error.

These experiments were carried out on equipment of the same type as the experiments whose results are shown in Fig. 1; for visualization of the process, the equipment was placed with its transparent internal face along the axis of the end row of the apertures of an array lying along the corner of a square. As a result, half the area of the aperture was covered by the wall and a system of semiinfinite nozzles (apertures) with the plane face toward the equipment wall was formed. The used arrays differed in the diameter of the apertures and the steps between them and, therefore, in their useful cross section; sand and nitroammophosph of different fractions were used as the material of the layer.

A detailed description of the results of these experiments and purely engineering conclusions and recommendations, which follow from them, is beyond the scope of the present work and will be discussed in a subsequent article. Here it is pertinent to stress only that the development of jets forming above the apertures of arrays proceeds according to the same general scheme as the development of a system of jets injected into an independently fluidized layer. The results obtained in experiments with these arrays can be actually used with high accuracy in the analysis of the zone near the array and of the processes of primary coalescence of bubbles and formation of piston-type gas layers in real equipment.

NOTATION

C, C', c, parameters in (1)-(4); D, instantaneous diameter of the bubble; D_0, initial diameter of the bubble; d, diameter of the particles of the layer; H, height of the layer or height of the level of primary coalescence; H_0, height of generation of bubbles; k, the ratio of the diameter of zone of circulation of particles to the bubble diameter; t, step between apertures or nozzles; t_m, minimum step corresponding to coalescence at level H; U, initial velocity of the jet; v, volume of the bubble; x, height of jet flare.

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