EFFECT OF A GAS STREAM ON THE EFFLUX OF LOOSE MATERIAL

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The article reveals the nature of the effect a gas stream has on a dynamically unstable arch and correspondingly on the efflux of loose material.

Installations with concurrent and countercurrent motion of material and gas are finding application in the economy. It is therefore of interest to examine the possibility of controlling the motion of a solid layer by a stream of gas used for processing the material, thus eliminating the use of mechanical unloading devices.

To reveal the physical pattern of the efflux of loose material under conditions of its interaction with a gas stream, the release of millet with 1.6-2.5 mm grain size was filmed on a transparent model, 300 × 60 × 5 mm in size, by a film camera SK-16 at a speed of 250 frames/sec. The gas was supplied in the form of a stream exerting uniform pressure on the surface of a dynamically unstable arch forming above the outlet opening [1], and in the form of a gas jet through a nozzle situated below the outlet opening. The ratio of the nozzle diameter to the length of the outlet slit changed within the range of 0.04-0.18. Observations of the efflux of millet, agglomerate, and limestone with grain size of 1.6-2.5 mm showed that with relatively low efflux speeds of air from the nozzle, when the ratio $V_c/V_{cr} \leqslant 20$ and $S_c/S_0 \geqslant 0.38$, the nature of the efflux of the loose material corresponds to its efflux in the countercurrent of a low-speed gas stream uniformly acting on a dynamically unstable arch. As a result of the examination of the film it was established that with increasing speed of the gas, the rate of mutual rotation of the particles of the material slows down, and the mass efflux speed of the material also decreases. The point is that the torque causing mutual rotation of two adjacent particles situated on a dynamically unstable arch is equal to $M_1 = T_1 r_1 - T_2 r_2$. If we take it that $r_1 = r_2 = r$, we obtain

$$M_1 = (T_1 - T_2)\, r \quad \text{or} \quad M_1 = T_1 \left(1 - \frac{T_2}{T_1}\right) r. \tag{1}$$

In case of uniform action of a gas stream from below on a dynamically unstable arch, an additional force F appears whose direction (Fig. 1) coincides with the direction of the frictional force between the particles, consequently:

$$M_2 = T_1 \left[1 - \frac{(T_2 + F)}{(T_1 + F)}\right] r. \tag{2}$$

It is easy to see that with increasing force F, i.e., speed of the gas countercurrent, the ratio $(T_2 + F)/(T_1 + F)$ increases, and the value of $1 - (T_2 + F)/(T_1 + F)$ decreases. As a result, the torque decreases, as does also the rate of mutual rotation of the particles of the material, the frequency of destruction (formation) of dynamically unstable arches, and consequently, the efflux speed of the material. Finally, when a certain gas speed is attained so that the ratio $(T_2 + F)/(T_1 + F) \to 1$, the torque becomes equal to zero.

It should be pointed out that an increase in the speed of the concurrent gas flow up to a certain magnitude causes a decrease in the ratio $(T_2 - F)/(T_1 - F)$, and consequently an increase of the torque, the rate of mutual rotation of particles, the frequency of destruction (formation) of dynamically unstable arches, and the efflux of speed of the material.

At the ratio $V_c/V_{cr} > 20$ and $S_c/S_0 < 0.38$, the frequency of destruction of the dynamically unstable arches increases. Through the transparent wall of the model it can be clearly seen how the jet "breaks" the arch, i.e., knocks upward one or several particles of loose material at the place where it touches the surface of the dynamically unstable arch, and as

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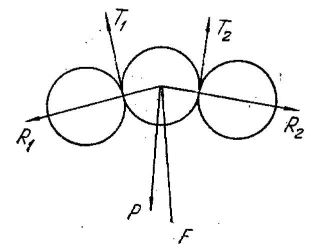

Fig. 1. Diagram of the forces acting on a system of spheres forming a dynamically unstable arch. Force F is directed upward.

a result, sliding occurs and the particles are compelled to rotate slightly. It is characteristic that in this case the mass efflux speed of the material decreases because the circulation of the particles knocked out by the jet causes a reduction of the surface of the dynamically unstable arch through which the higher-lying particles of the layer pass and which in the final analysis, other conditions being equal, determines the efflux speed of the loose material [1]. However, although with increasing speed of the air jet, the frequency of destruction (formation) of a dynamically unstable arch increases, and though it should consequently be expected that the mass efflux speed of the material increases, the fact is that it decreases. This is due to the prevalent effect of the reduced surface of the arch relative to the increased frequency of its destruction on the efflux speed of the material. When the speed of the air jet increases further to 40 or 50 m/sec, so that it penetrates more deeply into the bulk of the loose material, the number of particles moving through the surface of the arch increases, the surface of the dynamically unstable arch changes (increases), the frequency of destruction of the arches increases, and as a consequence the mass efflux speed of the loose material increases. When the speed of the jet increases to more than 50-70 m/sec at the place of its impact on the surface of the arch, a zone of circulation forms above the outlet opening which obeys its own laws [1].

The results of high-speed filming (Fig. 2) showed convincingly that the supply of a certain amount of air in the form of a stream uniformly acting on a dynamically unstable arch and of a high-speed jet does not change the essence of the efflux mechanism of material passing through the stage of destruction and formation of dynamically unstable arches.

It was established that when the speed of the air jet is low, the number of particles passing through the surface of the dynamically unstable arch is smaller than in the case of gravitational efflux of the material. Examination of the film shows that the frequency of destruction (formation) of dynamically unstable arches in the case of minimum efflux speed is reduced by almost half. The results of determining the mass flow rate of material by the weight method showed that it is 46% of the speed corresponding to gravitational efflux (Fig. 3). With increasing speed of the jet, the frequency of destruction (formation) of dynamically unstable arches increases, and this leads to increased efflux rate of the loose material (Fig. 3).

To study the process of efflux of loose material upon interaction with a gas stream in more detail, investigations were carried out on a laboratory model [2], and additional elements in it were nozzles for feeding gas in the form of jets into the layer of loose material. The design of the model made it possible to change the distance between the end face of the nozzle and the plane of the outlet opening, and consequently also between the former and the surface of the dynamically unstable arch, and also to change the place at which the jet impinged on the surface of the latter. Investigations were carried out with millet, limestone, agglomerate, coke of grain size 1.6-2.5 mm, at a ratio D_0/d_k = 5-50 and with different gases: hydrogen, helium, air. The experiments confirmed that the process of efflux of loose material acted upon by a gas stream does not depend only on the quantity and speed of the gas but also on the nature of its action on the dynamically unstable arch [3,4].

The obtained results make it possible to shed light on the nature of the dependence of the magnitude and sign* of the gas pressure drop at the outlet opening, including the pressure

*Positive when the gas pressure above the opening is higher than below it, and negative when it is the other way around.

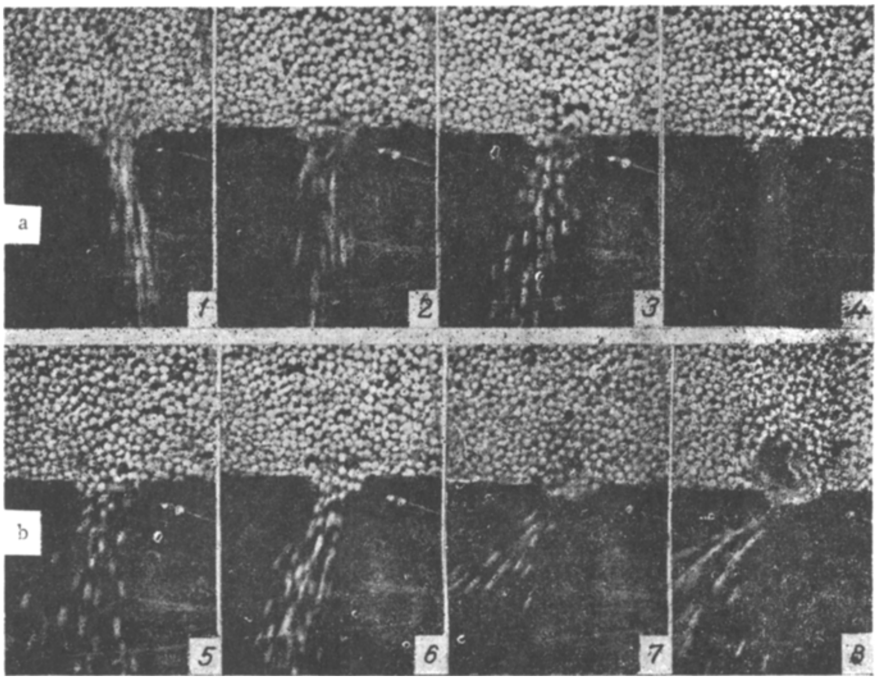

Fig. 2. High-speed photographs of the outflow of millet with a countercurrent of gas uniformly acting (a) on a dynamically unstable arch, and in the form of a gas jet (b) (length of the outlet opening is 15 mm): 1) $Q_g = 0\ m^3/h$; 2) 0.21; 3) 0.42; 4) 0.51; 5) 0.21; 6) 0.42; 7) 0.51; 8) 1.10 m^3/h.

drop at the dynamically unstable arch, on the change in the speed of the gas jet (Fig. 4), and to establish a correlation between the pressure drop and the mass flow rate of the material (Fig. 5). At first a relatively small increase in the speed of the gas jet reduces the rate of mutual rotation of particles and causes an increase in the negative pressure drop (Fig. 4), and this leads to reduced mass flow rate of the material (Fig. 5, curve AB).

The subsequent increase in the speed of the jet increases its kinetic energy to a value that suffices for destroying a dynamically unstable arch and for considerably changing the aerodynamic characteristics within its bulk (Fig. 4). On account of the circulation of the particles knocked out of the dynamically unstable arch, its surface is simultaneously reduced and the efflux rate of the materials decreases (Fig. 5, curve BC). As was shown above, a further increase in the speed of the gas jet leads to an increase in the frequency of formation (destruction) of dynamically unstable arches and increased mass flow rate of the material (Fig. 5, curve CD). In turn, on account of the limited gas permeability of the layer,

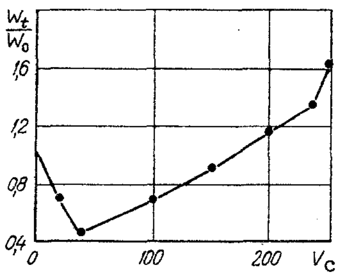

Fig. 3. Dependence of the ratio of the mass flow rate of millet upon gas supply to the model W_t (kg/sec) to the mass flow rate corresponding to gravitational mass flow rate W_0 (kg/sec) on the speed of the air jet V_c (m/sec) (length of the outlet opening is 15 mm).

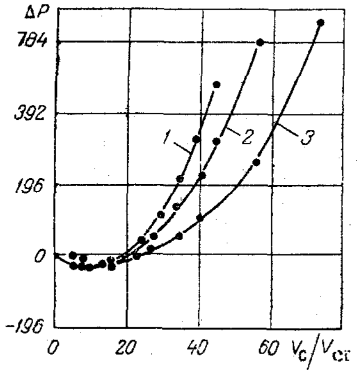

Fig. 4

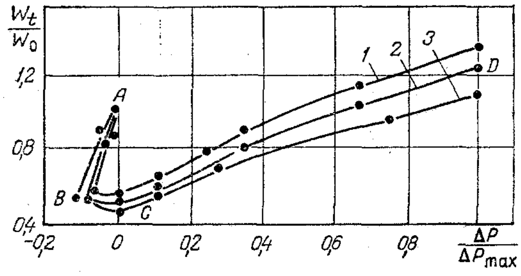

Fig. 5

Fig. 4. Change in the magnitude and sign of the gas pressure drop at the outlet opening ΔP, mm water column, in dependence on the ratio of the speed of the gas jet V_c, m/sec, to the critical gas speed V_{cr}, m/sec, with different distances between the end face of the nozzle and the plane of the opening (diameter of the outlet opening 15 mm, agglomerate): 1) 12 mm; 2) 20; 3) 28.

Fig. 5. Dependence of the relative flow rate of agglomerate W_t/W_0 on the magnitude and sign of the relative gas pressure drop at the outlet opening $\Delta P/\Delta P_{max}$ with different distances between the end face of the nozzle and the plane of the opening of 15-mm diameter (ΔP is the current pressure drop with the given arrangement of supplying gas to the model, mm water column): 1) 12 mm; 2) 20; 3) 28.

with increasing speed of the gas jet and increasing amount of gas, an ever larger part of the gas stream is deflected to the side of the outlet opening, and then the positive pressure drop increases (Fig. 4).

Thus, the mechanism of efflux of loose material through an opening situated in a horizontal plane, under conditions of its interaction with a gas stream, can be pictured as follows. The gas stream, acting uniformly from below on a dynamically unstable arch, reduces the rate of the mutual rotation of particles of material at the instant of formation of a dynamically unstable arch because it reduces the torque of adjacent particles and exerts additional pressure from below on the surface of the arch. Thereby the gas stream increases the time of destruction and formation of the arch, and this leads to reduced mass flow rate of the material. In addition to that, the counterflow of gas slows down the falling of the particles of material. When the gas stream attains its critical speed where the force with which it acts on the arch is considerably larger than the frictional force between the particles of the material, causing torque and their mutual rotation, the feeding of gas is an obstacle to the destruction of the dynamically unstable arch and causes hanging of the loose material. With increasing speed of the gas in the entire investigated range, the negative gas pressure drop on the dynamically unstable arch increases. The effect of the gas stream on the process of destruction (formation) of dynamically unstable arches, which consists in reducing the torque of adjacent particles, is constant up to loss of contact between particles. In distinction, the effect of a gas stream pressing the particles forming a dynamically unstable arch against the material situated above and thus reducing the torque of these particles is short-lived. It makes itself felt only at the first instantaneous formation of a dynamically unstable arch and disappears when the arch begins to move and to lose contact with the higher-lying (newly formed) arch, without affecting the process of destruction itself.

An increase in the speed of the concurrent gasstream (pressurized discharge) up to a certain magnitude increases the rate of the mutual rotation of the particles of material because the gas energy increases the torque of the particles, and consequently the frequencies of destruction (formation) of dynamically unstable arches, and also the flow rate of the material.

It should be noted that the feeding of a considerable amount of gas causes change in the mechanism of discharge of the material. In this case, the gas stream, having high speed and energy, destroys the dynamically unstable arch, and this, with increasing gas flow rate, leads naturally to increased discharge rate of the material. Consequently, supply of a considerable amount of gas with sufficiently large diameter of the outlet opening causes the so-called piston regime of motion of the material. Increased gas supply leads in all cases to increased positive gas pressure drop on a dynamically unstable arch.

The supply of gas in the form of jets directed upward from below on a dynamically unstable arch, at the beginning, when their speed and energy are small, has the same effect on the discharge of material as a gas stream acting uniformly from below on a dynamically unstable arch, i.e., it reduces the discharge rate of loose materials. Increased gas supply causes an increase of the negative gas pressure drop on the dynamically unstable arch. When the speed of the gas jets is further increased, there is an instant when the energy of the jet is sufficient to knock out one or several particles from its surface, and this leads to the destruction of the arch. From this instant on, an increase in the speed of the gas jets leads to an increase in the frequency of destruction (formation) of dynamically unstable arches, and consequently to increased discharge rates of the loose material. It is characteristic that a "break-through" of the gas jets across the surface of the dynamically unstable arch causes ejection of gas from the space below the arch, and this entails the redistribution of the gas pressure and a change in the sign of the gas pressure drop on the dynamically unstable arch and an increase of its absolute value with increasing speed of the jet.

Consequently, the discharge of loose material through an opening situated in a horizontal plane can be successfully controlled by the direction, energy, and degree of localization of the effect of a gas stream acting on a dynamically unstable arch. Measurement of the magnitude and sign of the gas pressure drop at the outlet opening, including the pressure drop on the dynamically unstable arch, provides the possibility of controlling the discharge of loose material, no matter what method is used to supply gas to the layer. This makes it possible to use, with satisfactory accuracy, a number of correlations, among them gas pressure drop on a dynamically unstable arch, for determining the discharge rate of loose material, specifically Eq. (27) [1].

NOTATION

V_c, efflux speed of the gas jet from the nozzle; V_{cr}, gas speed in the outlet opening at which the material begins to hang; S_0, S_c, area of the outlet opening and of the cross section of the gas jet, respectively, upon impinging on the surface of a dynamically unstable arch; T_1, T_2, frictional forces between adjacent particles of loose material; r_1, r_2, radii of adjacent particles on a dynamically unstable arch; F, force of the gas pressure on particles of material on a dynamically unstable arch; P, force of gravity; R_1, R_2, reactions of the support.

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