CIRCULATION OF THE SOLID PHASE THROUGH A VERTICAL GAS JET INJECTED INTO A LAYER OF GRANULAR MATERIAL

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A method is developed for determining the mass of particles circulating through a vertical gas jet. On the basis of experimental data dependences are obtained for determining the circulation of particles and the velocities of their motion in the jet.

The range of use of apparatus containing a solid moving or stationary medium is extremely large. Jets are introduced for different purposes and with different devices: gas-distribution grids, sprayers, pneumatic feeders, submerged burners, etc. Here in all cases the determination of the mass of particles circulating through the gas jet has fundamental importance, since the amount of particle circulation determines the intensity of the processes of heat and mass transfer.

Dependences determining the particle distribution in cross sections of a jet, the shape of the jet channel, and the velocity of particle motion in the jet are proposed in the literature on the basis of test data obtained with the help of a strain-measuring probe [1] or by photography of a semibounded jet [2]. The advantages and drawbacks of the proposed methods are sufficiently obvious, but neither method allows one to obtain any circulation laws and they only provide the possibility of a comparative analysis of the particle distributions over cross sections of the jets.

Investigations of a semibounded jet in the mode of local fountaining and in the steady mode showed that particles injected by the jet in the lower half of the bed are transported strongly to its top and leave it there, falling onto the surface of the bed [3, 4]. In this case stable boundaries of the jet, along which the descending motion of bed particles occurs, are retained. This made it possible to develop a new means of determining the number of particles entering a vertical gas jet injected into a bed of granular material [5].

Its essence consists in dropping a perforated disk with a central opening equal to the maximum width of the jet onto the surface of the fluidized or stationary bed coaxially with the jet. Particles enter the jet from the bed, are caught by the gas, and are carried by it through the opening of the disk into the space above the bed, where they are transported in a radial direction and fall onto the surface of the disk. As a result of this one observes the outflow of particles from below the disk into the jet and the disk starts to sink, with the rate of its motion being proportional to the number of particles coming from below the disk. By determining the time of descent of the disk one calculates the mass of particles entering the jet per unit time.

In the present report we used the apparatus shown in Fig. 1 to investigate the mass of particles passing through the jet per unit time. The apparatus consists of a transparent cylindrical housing of plastic with an inner diameter of 125 mm and a height of 600 mm placed on a steel gas chamber. A gas-distribution grid with an open cross section of 6.4% and openings 1.0 mm in diameter with a spacing of 4 mm was installed to distribute the gas in the bed of granular material. The apparatus includes a replaceable perforated disk with a central opening made of a Kapron mesh and equipped with a paper guide sleeve with centering skirts, providing coaxiality of the opening in the disk with the nozzle during the movement of the disk. The material of the bed and its height above the nozzle, the diameters of the particles and the nozzle, the fluidization number, and the velocity of discharge from the jet were varied while performing the investigations.

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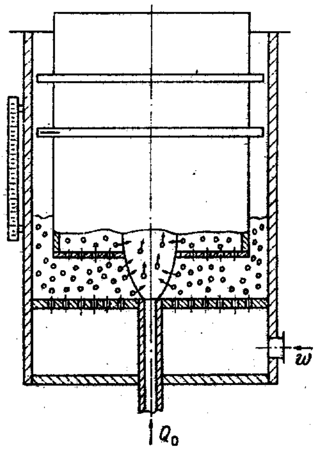

Fig. 1

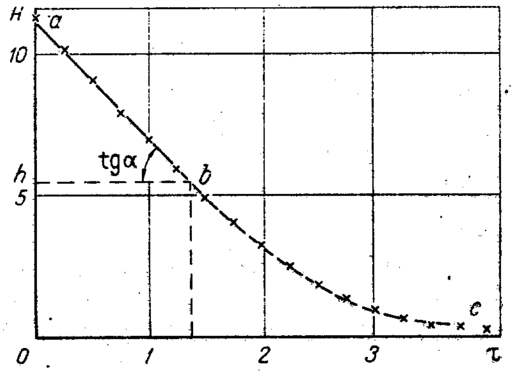

Fig. 2

Fig. 1. Schematic diagram of apparatus for the investigation of particle circulation.

Fig. 2. Graph of motion of the disk (polystyrene, d_e = 2.8 mm, H_0 = 110 mm). H, cm; τ, sec.

The air expended on fluidization was measured with a chamber diaphragm and a liquid manometer. The rate of motion of the disk was recorded by movie photography at a speed of 24 frames/sec. The mutual arrangement of the measurement scale and the indicator mark permitted the determination of the time of descent of the disk to any height. A characteristic graph of the disk motion is presented in Fig. 2. As seen from the figure, the disk moves with a constant velocity in section a, b and with deceleration in section b, c, which indicates that the main mass of particles enters the jet in the immediate vicinity of the nozzle, namely, in the interval from 0 to h (zero corresponds to the level of the nozzle cut), i.e., in section b, c. Then only the transport of particles to the surface of the bed occurs in section a, b. The rate of entry of particles into the jet is uneven over the height of the jet and increases as the nozzle is approached. We introduce the average rate of entry of particles into the jet (assuming that their motion takes place in the transverse direction) in the form

$$u_{av} = \frac{1}{h} \int_0^h u(z)\, dz. \tag{1}$$

The mass of particles passing through the jet above the level z per unit time can be calculated from the equation

$$q = 2\pi b h \rho_s (1-\varepsilon)\, u_{av}. \tag{2}$$

When the disk sinks to a height dz in a time dτ material enters the jet in an amount dqτ. When the area of the apparatus is S, we have

$$q d\tau = -S\rho_s (1-\varepsilon)\, dz. \tag{3}$$

With allowance for (2), we obtain

$$\frac{dz}{d\tau} = -\frac{2\pi b u_{av} h}{S} = -\operatorname{tg}\alpha, \tag{4}$$

tan α being the tangent of the inclination angle of the straight part of the graph to the abscissa.

It is easy to obtain the numerical value of the velocity u_{av} from (4). For the case presented in Fig. 2, u_{av} = 0.41 m/sec and the flow rate of material through the jet per second is q = 0.28 kg/sec (the porosity of the bed was taken as 0.4).

In the section $0 < z \leqslant h$ the mass of the particles passing through in the jet above the level z is determined from the expression

$$q = \rho_s (1-\varepsilon)\, 2\pi b \int_0^z u(z)\, dz. \tag{5}$$

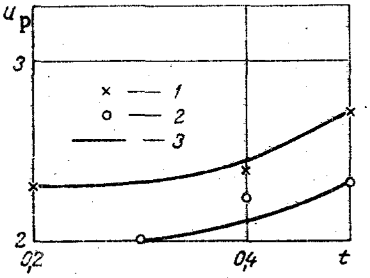

Fig. 3

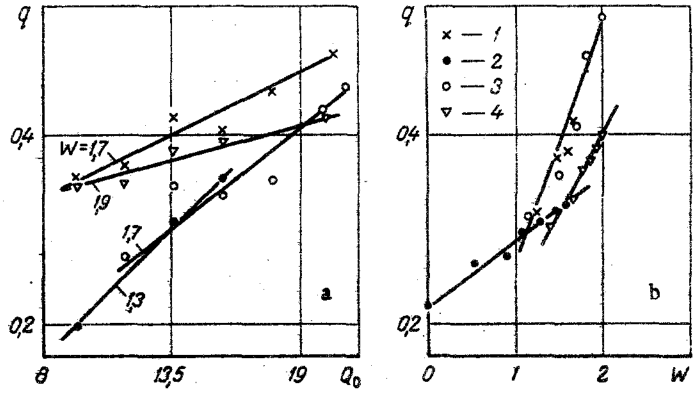

Fig. 4

Fig. 3. Profile of particle velocity along the axis of the fountain (H_0 = 100 mm, silica gel): 1) d_e = 3 mm; 2) d_e = 4 mm; 3) from Eq. (11). u, m/sec.

Fig. 4. Mass of particles thrown up by the jet as a function of gas velocity, d_0 = 6 mm: 1) Al–Si, d_e = 2.2 mm, H_0 = 130 mm; 2) cylindrical polyethylene, d_e = 2.8 mm, H_0 = 110 mm; 3) glass beads, d_e = 1 mm; 4) polystyrene, d_e = 2.8 mm, H_0 = 110 mm; Q_0 = 13 m^3/h = const.

The velocity of particles from the bed into the jet in this section is assigned in a first approximation in the form

$$u(z) = a(h - z), \tag{6}$$

and then, using Eqs. (3), (5), and (6), we obtain

$$\frac{dz}{d\tau} = -\frac{z(2h - z)\,\mathrm{tg}\,\alpha}{h^2} \quad (0 < z \leqslant h). \tag{7}$$

Solving (7) for z, we have

$$z = \frac{2h}{1 + \exp(2\tau\,\mathrm{tg}\,\alpha/h)}. \tag{8}$$

The calculating curve based on Eq. (8) is plotted in Fig. 2 with a dashed line.

Equation (6) can be used to determine the velocity of particle rise in the fountain in the lower half of the bed (section bc). The equation of motion of the particles, with allowance for the variation of their concentration n_z over the height of the fountain, according to [6] has the form

$$\frac{d(n_z \cdot u_p)}{d\tau} = \xi n_z \rho_g \frac{(u_g - u_p)^2}{4 d_e \rho_s} - \frac{\rho_s - \rho_g}{\rho_s} n_z g. \tag{9}$$

On the basis of test data presented in [1] on the velocities of gas and particles in the fountain, in a first approximation we can take

$$u_g^2 \gg 2u_g u_p - u_p^2, \quad u_g \sim 1/z^{1/3} \text{ and } \xi = 0.45 \quad [7],$$

and then with allowance for Eq. (6) we have from (9)

$$u_p \frac{du_p}{dz} + u_p\left(\frac{1}{z} - \frac{1}{H_0 - z}\right) = 0.34\,\frac{\rho_g}{\rho_s d_e}\left(\frac{c}{z^{1/3}}\right)^2 - \frac{\rho_s - \rho_g}{\rho_s} g. \tag{10}$$

The integration constant in (10) is determined at t = 0.5, and then $u_p = u_c$ and the solution of (10) is reduced to the form

$$u_p^2 = \frac{u_c^2 - 1.22kc^2H_0^{1/3}\left[1 - t^{7/3}(11.3 - 15.8t + 6.1t^2)\right]}{16t^2(1-t)^2} + \frac{5.12gH_0(\rho_s - \rho_g)\left[1 - t^3(20.6 - 31.2t + 12.5t^2)\right]}{16\rho_s t^2(1-t)^2}, \tag{11}$$

$$t = z/H_0; \quad k = 0.336\rho_g/\rho_s d_e.$$

A comparison between values computed from (11) and the test data of [1] is presented in Fig. 3. The numerical values of u_c were taken directly from the experimental results, and c is also an experimental constant, depending on the velocity profile along the axis of the fountain; here c = 4.9 [1]. In accordance with (2) and (4), the mass of particles thrown up by the jet per unit time is determined from the equation

$$q = S\rho_s' (1 - \varepsilon) \operatorname{tg} \alpha. \quad (12)$$

An experiment performed by the described method with bed heights of from 70 to 150 mm with the injection of air at t = 20°C into a bed of particles with $10^5 < Ar < 10^6$ showed that tan α hardly depends on the height and increases with an increase in the Archimedes number Ar by the law $\tan \alpha \sim Ar^{0.4}$.

Dependences of q on the fluidization number and on the jet velocity are presented in Fig. 4a, b. The increase in the mass of circulating particles with an increase in w occurs as a result of the decrease in the viscosity of the bed. With an increase in the velocity of the gas supplied to the jet, the viscosity of the bed also decreases as a result of the gas injection into the surrounding material, being the more intense, the less the preliminary fluidization of the bed.

Actually, the straight line approximating the test values of q gives a steeper rise with an increase in the flow rate of air supplied to the jet with w = 1.3 than with w = 1.7 (Fig. 4a).

In all the tests set up the flow of material into the jet (point b in Fig. 2) began from half the height of the bed; the deviation did not exceed 15%. It was shown in [6] that from approximately half the bed height the gas velocity in the fountain is close to the particle hovering velocity. Consequently, in the upper half of the fountain a certain share of the ascending particles exchanges momentum with particles entering radially from the bed and not having a significant vertical velocity component. Such collisions occur in the immediate vicinity of the bed surrounding the fountain. The overwhelming majority of the particles rising upward after a collision penetrates into the bed, while the mass of the jet generally remains constant in section ab. Thus, particles from all cross sections of the bed are present in the mass of material leaving the jet, but their concentration in the upper half of the fountain does not vary.

In conclusion, we note that the circulation of the solid phase in a jet not breaking through the bed can be determined by the method described above with some special construction features. An experiment performed for such a jet showed that the circulation of particles through a jet not breaking through the bed and the circulation through a fountain coincide qualitatively.

NOTATION

τ, current time; z, longitudinal coordinate; H_0, bed height; h, coordinate of boundary of injection zone of jet; $t = z/H_0$, dimensionless coordinate; u(z), radial particle velocity at the jet boundary; u_{av}, particle velocity introduced in (1); u_p, velocity of particle rise at the fountain axis; u_c, particle velocity at t = 0.5; u_g, gas velocity along jet axis; q, mass flow rate of particles through the jet; ρ_s, ρ_g, densities of particles and gas, respectively; d_e, equivalent particle diameter; Q_0, gas flow rate to jet; S, cross-sectional area of apparatus; ε, bed porosity; n_z, particle concentration in a cross section at the level z; ξ, coefficient of resistance; *a*, coefficient introduced in (5); C, coefficient introduced in (10); W, fluidization number; g, free-fall acceleration; $Ar = (gd_e^3/\nu^2)[(\rho_s - \rho_g)/\rho_g]$, Archimedes number; b, half-width of gas jet.

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