# DISCHARGE OF A GAS JET INTO A STATIONARY BED OF GRANULAR MATERIAL

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An experimental study is made of the discharge of a gas jet into a stationary bed of granular material. The physical pattern of development of the jet is established and an approximate method is developed for calculating the dimensions of the gas tongue.

In a number of cases in the development of equipment containing a stationary bed of solid material it becomes necessary to know the conditions of entry of gas into the bed, since they have an important effect on the processes being carried out [1, 2]. In connection with this the interest of investigators in the study of the development of jets in a stationary bed of granular material increases more and more [1, 3-6]. The published data are entirely inadequate for the development of engineering methods of calculation, however, and therefore it is necessary to extend the experimental studies of a gas jet in a stationary bed of granular material.

The study was performed on a laboratory installation with two pieces of apparatus: of rectangular cross section 95 × 125 mm in size and cylindrical with a diameter of 125 mm. A semibounded air jet discharging along a transparent wall was studied in the apparatus of rectangular cross section. Unbounded air jets discharging from nozzles of $d_0 = 4, 6, 8$, and 10 mm mounted at the center of the apparatus were studied in the cylindrical apparatus. In both cases the jet was isothermal.

The study provided for visual observations of the behavior of the semibounded jet and velocity measurements with an accuracy of 2.6% with pneumatic measuring tubes which could be moved with a coordinating mechanism [6, 7] along the cross sections and the axes of the semibounded and unbounded jets. The discharge velocity of the jets was varied from 2 to 200 m/sec and the height of the stationary bed was varied from 50 to 250 mm. The discharge velocity was measured with rotameters with an accuracy of 3%. The height of the bed was determined with a measuring rule with an accuracy of 0.5 mm. The characteristics of the solid particles used are presented in Table1.

Visual observations showed that at a certain discharge velocity for the given particles a spherical cavern with circulating movement of the solid particles within it forms near the nozzle (Fig. 1a). We call the jet discharge velocity at which this effect appears the velocity of circulation onset ($u_c$). A further increase in the discharge velocity of the jet leads to the formation of a gas tongue almost free of solid particles and around this tongue a zone of circulation of the solid particles (Fig. 1b). The movement of the particles in the circulation zone occurs owing to the ejecting action of the jet. Drawn in near the mouth of the jet, the particles move along the boundaries of the gas tongue, being thrown back into the upper part of the circulation zone, and then slowly settle into its lower part and are again drawn in by the jet. Special studies using marked particles showed that the exchange of solid particles between the circulation zone and the rest of the stationary bed is slight and occurs only through the particles immediately adjacent to the boundaries of the zone.

A further increase in the discharge velocity leads to growth in the size of the gas tongue and the formation of a local fountain effect, which is preceeded by the appearance at the surface of the stationary bed of a characteristic "hill" (Fig. 1c). This is observed when the length of the gas tongue becomes equal to half the height of the bed:

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TABLE 1. Characteristics of Granular Materials

| Material | Screen grade | Equivalent diameter, m | Density, kg/m³ | Shape and surface of particles |
|---|---|---|---|---|
| Aluminosilicate catalyzer | 2,0—2,5 | 2,24 | 1136 | Spherical smooth |
| The same | 2,5—3,0 | 2,64 | 1126 | The same |
| The same | 3,0—4,0 | 3,46 | 1136 | » |
| The same | 4,0—5,0 | 4,46 | 1142 | » |
| Polystyrene | 0,63—0,74 | 0,68 | 1050 | » |
| The same | 0,8—1,0 | 0,89 | 1050 | » |
| The same | 1,0—2,0 | 1,41 | 1050 | » |
| Polyethylene |  | 4,3 | 950 | Cylindrical smooth |

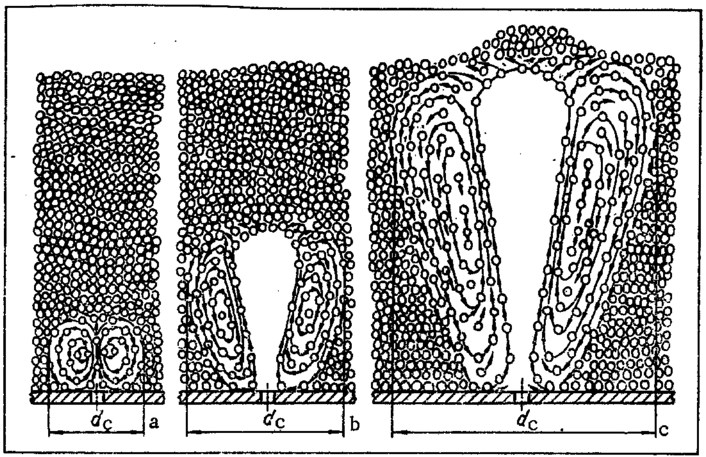

Fig. 1. Physical pattern of development of a gas jet in a stationary bed of granular material: a) $u_0 = u_c$; b) $u_0 > u_c$; c) $u_0 = u_t$.

$$l_t = 0.5 l_{bed}. \tag{1}$$

The jet discharge velocity at which the appearance of this "hill" is observed we have called the minimum fountain-effect velocity [8]. For the given particles its value depends on the height of the bed.

Measurement of the velocity of circulation onset with a gradual increase and decrease in the flow rate of gas through the nozzle showed that this velocity does not depend on the height of the bed if it is determined through a decrease in the gas flow rate, while it does depend on the height of the bed if it is determined through an increase in the gas flow rate. The results of such measurements during discharge of a jet from a nozzle with $d_0 = 6$ mm into a bed of spherical particles of polystyrene with $d_p = 1.0$–$2.0$ mm are presented in Table 2. The difference in the velocities of circulation onset during an increase and a decrease in the flow rate of gas through the nozzle can be explained by the inertia of the solid particles and by friction between the particles, which depends on the pressure of the upper part of the bed. It was also established that the velocity of circulation onset depends on the size, shape, and density of the particles. An analysis of the data on the determination of the velocity of circulation onset during a decrease in the velocity of discharge of a jet from a semibounded nozzle with $d_0 = 6$ mm for particles with about the same surface roughness made it possible to obtain the function

$$\mathrm{Fr}_c = 11.4 \cdot 10^{-5} \mathrm{Ar}^{1.46}, \tag{2}$$

which was verified with

$$1.1 \cdot 10^3 \leqslant \mathrm{Fr}_c \leqslant 112.5 \cdot 10^3; \quad 1.17 \cdot 10^5 \leqslant \mathrm{Ar} \leqslant 34.0 \cdot 10^5.$$

The error in calculations based on the function (2) does not exceed 15%.

The geometrical characteristics of the gas tongue and the circulation zone were also determined in these studies. For the semibounded jet these characteristics were measured with an accuracy of 0.5 mm

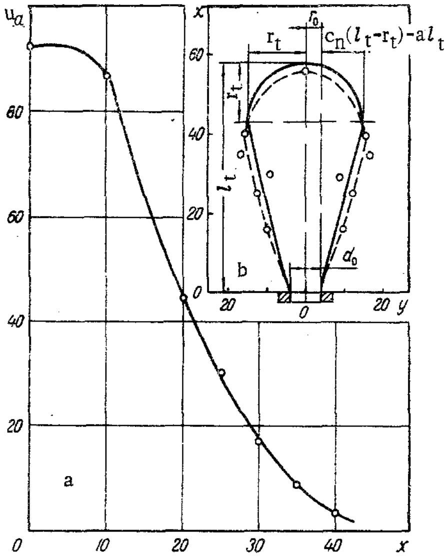

Fig. 2

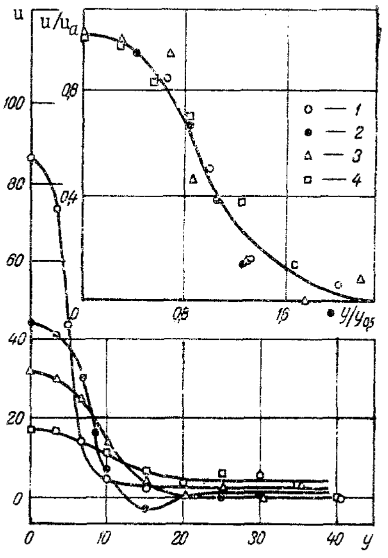

Fig. 3

Fig. 2. Velocity variation along the axis of an unbounded jet discharging from a nozzle with $d_0$ = 8 mm at a velocity $u_0$ = 92 m/sec into a stationary bed of spherical aluminosilicate catalyzer with $d_p$ = 2.0-2.5 mm (a) and comparison of the calculated and experimental contours of the gas tongue of a jet discharging from a nozzle with $d_0$ = 8 mm at a velocity $u_0$ = 108 m/sec into a stationary bed of aluminosilicate catalyzer with $d_p$ = 2.0-2.5 mm (b). u, m/sec; x, y, mm.

Fig. 3. Velocity variation in cross sections of an unbounded jet discharging from a nozzle with $d_0$ = 8 mm at a velocity $u_0$ = 92 m/sec into a stationary bed of aluminosilicate catalyzer with $d_p$ = 2.0-2.5 mm: 1) x = 10 mm; 2) 20; 3) 25; 4) 30.

through the transparent wall of the apparatus using a measuring rule, while for the unbounded jet they are determined from the measurement data on its velocity field. The latter became possible after it was established that the velocity at the boundary of the gas tongue is close to the velocity of wandering of the solid particles. On the basis of this fact the length of the gas tongue and its half-widths in different cross sections of the jet were found from graphs of the velocity distribution along the axis of the jet and in its cross sections (Figs. 2 and 3) as the abscissas of the points having a velocity equal to the velocity of wandering.

The studies showed that the laws of the development of a jet in a stationary bed are close to the laws of development of a jet in a fluidized bed [9, 10]. Thus, from the analysis of the effect of the parameters of the jet and the bed on the dimensions of the gas tongue it follows that, as in the case of a fluidized bed, its dimensions increase with an increase in the discharge velocity and the nozzle diameter and with a decrease in the particle diameter. The velocity profiles in cross sections of a jet in a stationary layer have the same form as in the case of a jet in a fluidized bed (Fig. 3), and they are also similar in dimensionless coordinates. The visual observations of the nature of the development of a jet in a stationary bed also permit one to assume its coincidence with the development of a jet in a fluidized bed. In fact, with the discharge of a jet into a stationary bed a circulation zone whose density is considerably less than the density of the main part of the bed forms around the gas tongue. The solid particles which lie within it move with high velocity along the gas tongue, forming a narrow two-phase boundary layer analogous to the gas–solid particle zone of a jet in a fluidized bed [9, 10]. At some distance from the gas tongue the particles move in the opposite direction, interacting now with the stream of gas filtering from the jet.

On the basis of such concepts a jet in a stationary bed under the conditions of formation of a circulation zone can be considered in a first approximation as developing in a region of "local fluidization" of the stationary bed. Then the length of the gas tongue can be determined with an accuracy of 20% from the expression

$$l_t = \frac{u_0 r_0}{1.6 u_w c_n}, \qquad (3)$$

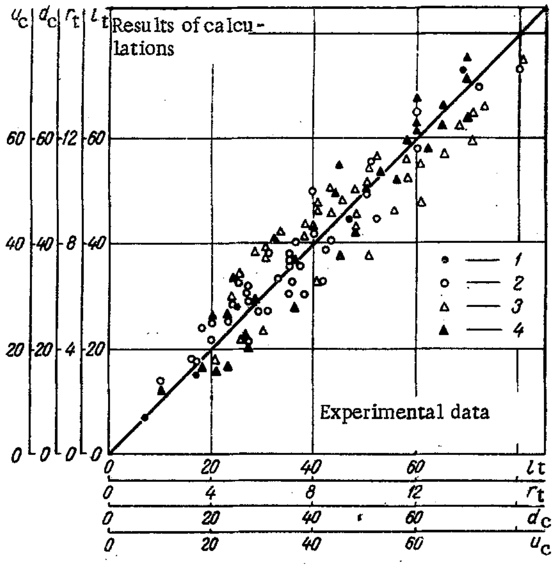

Fig. 4. Correlation graph of results of calculation based on Eqs. (2), (3), (5), and (6) and experimental data: 1) Eq. (2); 2) (3); 3) (5); 4) (6). $u_c$, m/sec; $l_t$, $r_t$, $d_c$, mm.

TABLE 2. Effect of Height of Stationary Bed on Velocity of Circulation Onset

| Height of bed, mm | Velocity of circulation onset, m/sec | |
|---|---|---|
| | increase in gas flow rate | decrease in gas flow rate |
| 50 | 39,1 | 16,2 |
| 60 | 46,0 | 16,4 |
| 90 | 92,5 | 17,3 |
| 120 | 92,0 | 16,7 |
| 160 | 96,0 | 16,0 |

which differs from the analogous expression for a jet in a fluidized bed [9, 10] in the value of the numerical coefficient in the denominator. In the present case the value of this coefficient was determined through experiment.

The coefficient of expansion of the jet ($c_n$) which enters into (3) was calculated from an equation of the approximate theory of discharge of a jet into a fluidized bed [9, 10]:

$$c_n = \frac{b_t}{x}\frac{u_a + u_w}{u_a - u_w} - \frac{r_0}{x}. \tag{4}$$

In this case the width of the gas tongue ($b_t$) and the velocity at the jet axis ($u_a$) were determined from the experimental velocity profiles in different cross sections of a jet discharging into a stationary bed. It was established that within the ranges of variation of the parameters of the jet and the bed which occur in these experiments the coefficient of expansion of the jet is approximately equal to $c_n = 0.8$.

The radius of the gas tongue of a jet in a stationary bed at the distance from the nozzle to the maximum cross section can be determined as (see Fig. 2b)

$$r_t = l_t \frac{c_n - a}{1 + c_n} + r_0 \frac{1}{1 + c_n}, \tag{5}$$

where $a$ is a coefficient which allows for the curvature of the boundary of the gas tongue. Its numerical value is about 0.4. The function (5) permits one to calculate with an accuracy of 30%.

The study of the semibounded jet also showed that the height of the circulation zone is comparable with the length of the gas tongue (Fig. 1b) (the difference does not exceed $1\text{-}2d_e$). For the determination of the maximum diameter of the circulation zone with an accuracy of 25% we obtained the empirical equation

$$d_c = 2.5 \cdot 10^{-2} d_0 \mathrm{Fr}^{0.63} \mathrm{Ar}^{-0.1}, \tag{6}$$

which is verified with

$$2.04 \cdot 10^4 \leqslant \mathrm{Fr} \leqslant 88.7 \cdot 10^4;\ 1.17 \cdot 10^5 \leqslant \mathrm{Ar} \leqslant 34.0 \cdot 10^5.$$

A comparison of the calculated and experimental contours of the gas tongue, which shows satisfactory convergence, is presented in Fig. 2b. A comparison between the results of calculations based on Eqs. (2), (3), (5), and (6) and the experimental data is presented in the correlation graph of Fig. 4.

## NOTATION

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|---|---|
| $d_0$, $d_p$, $d_e$ | are the nozzle diameter, diameter of solid particles, and equivalent diameter of solid particles; |
| $d_c$ | is the maximum diameter of circulation zone; |
| $l_{bed}$, $l_t$ | are the height of bed and length of gas tongue; |
| $u$, $u_0$, $u_c$, $u_w$ | are the velocity in current cross section of jet, jet discharge velocity, velocity of circulation onset, and velocity of wandering of solid particles; |
| $r_0$, $r_t$ | are the nozzle radius and maximum radius of gas tongue; |
| $x$ | is the longitudinal coordinate; |
| $y$ | is the current radius of jet; |
| $\rho_s$, $\rho_g$ | are the density of solid material and gas density; |
| $\nu$ | is the kinematic viscosity of gas; $Fr = u_0^2/gd_0$, |
| $Fr = u_0^2/gd_0$ | is the Froude number; |
| $Fr_c = u_c^2/gd_0$ | is the circulation Froude number; |
| $Ar = gd_e^3(\rho_s - \rho_g)/\nu^2\rho_g$ | is the Archimedes number. |

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