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GAS DISTRIBUTION IN A PACKED BED WITH JET GAS INJECTION

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This article examines the distribution of gas flows in the vicinity of a jet entering a packed bed. A qualitative explanation of the character of particle motion around the cavity is given.

The rate of heat and mass transfer processes in units with a packed bed is determined by the hydrodynamic situation in the bed – particularly by the distribution of gas-phase velocity [1]. Several studies have modeled the gas distribution in a granular bed [2-4]. However, these studies focused either on the so-called filtration regime of flow – when the gas flow does not form a cavity free of solid particles in the bed [2] – or on the spouting regime of jet injection [3]. The study [4] solved the problem of the gas distribution in a fixed granular bed as a special case of the gas distribution in a fluidized bed with jet gas injection and a bed aeration rate equal to zero. This approach to modeling the gas distribution in a fixed granular bed does not reflect the specifics of the problem or its differences from the problem for a fluidized bed, and it can be used only as a first approximation.

It was established experimentally [5] that the character of change in static pressure inside the cavity formed with jet gas injection into a fluidized or fixed granular bed is different in these two cases. In the jet in the fluidized bed, static pressure increases sharply only over a short initial section of the jet and remains nearly constant for most of its length. Thus, the assumption of a constant pressure in the jet entering a fluidized bed which was adopted in [4] can be considered valid. In a jet entering a fixed granular bed, static pressure increases over the entire length of the jet on the jet axis in accordance with a law which is close to linear, and it reaches its maximum value near the end of the cavity. Thus, the assumption of constancy of pressure inside the cavity cannot be adopted for a fixed bed.

Here we propose a model of gas distribution in the vicinity of a plane or axisymmetric jet in a fixed granular bed which is based on the assumption of a linear change in static pressure inside the jet channel.

Let a granular bed of height H be located in a plane or cylindrical unit of width or diameter 2R (Fig. 1). The gas jet is injected in the plane of the base of the bed $y = 0$ through a slit or circular opening of width or diameter 2a which is coaxial with the walls of the unit. The jet forms a cavity of height b in the bed, the boundary of this cavity being described by the equation $x^2/a^2 + y^2/b^2 = 1$. The chosen form of cavity is close to the shape actually seen in practice and differs from the shape assumed in [4]. It makes it possible to consider not only the height of the cavity, but also the size of the opening for entry of the gas. The latter is particularly important in the case of low gas velocities, when the height of the cavity becomes commensurate with the diameter of the nozzle. We will assume that the static pressure on the top boundary of the bed is constant and equal to zero, while inside the cavity it changes in accordance with a linear law with the coefficient K:

$$p = Ky \quad \left(\frac{x^2}{a^2} + \frac{y^2}{b^2} \leqslant 1\right). \tag{1}$$

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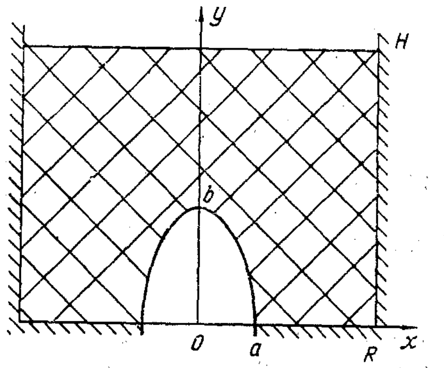

Fig. 1. Diagram of a jet in a unit with a granular bed.

As in [2-4], we assume that the porosity of the bed outside the jet is uniform, and that the gas flow in the bed obeys Darcy's law

$$\operatorname{grad} p = -\alpha \mathbf{U}. \tag{1}$$

Using the continuity equation and the conditions for impermeability of the walls of the unit and the gas-distributing grate, we obtain the problem for the gas pressure in the bed:

$$\begin{gathered} \Delta p = 0; \\ \frac{\partial p}{\partial x} = 0 \quad (x = \pm R); \quad \frac{\partial p}{\partial y} = 0 \quad (y = 0); \\ p = 0 \quad (y = H); \; p = Ky \quad \left(\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \right). \end{gathered} \tag{2}$$

We introduce the function for the filtration flow potential in the form of the formula

$$\varphi = \frac{p}{K} \tag{3}$$

and we obtain the problem for φ independent of α and K:

$$\begin{gathered} \Delta \varphi = 0; \\ \frac{\partial \varphi}{\partial x} = 0 \quad (x = \pm R); \quad \frac{\partial \varphi}{\partial y} = 0 \quad (y = 0); \\ \varphi = 0 \quad (y = H); \; \varphi = y \quad \left(\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \right). \end{gathered} \tag{4}$$

The problems for axisymmetric and plane flows differ only in the form of the Laplace equation. For an axisymmetric jet, the Laplace equation takes the following form in the transition to a two-dimensional Cartesian coordinate system

$$\frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial x^2} - \frac{1}{x} \frac{\partial \varphi}{\partial x} = 0.$$

Problem (4) cannot be solved analytically, so a finite-difference scheme [6] was used to determine φ. The resulting system of linear equations was solved by the Gauss—Seidel method.

Since problem (4) does not depend on the characteristics of the particles or the gas K and α, then with adherence to similarity laws for the geometric parameters a, b, H, and and R, the velocity fields obtained for different particles and gases will also be similar. However, when calculating actual values of gas velocity in a unit by means of Eqs. (1) and (3), it is necessary to assign the coefficients α and K. Whereas the coefficient α is one of the common characteristics of a granular material and is a known quantity for each specific case, the value of the coefficient K cannot be determined beforehand. We therefore proceed as follows. We solve problem (4) with assigned parameters a, b, H, and R, where the parameter b will be calculated from empirical formulas proposed in [5]. For an asymmetric jet

$$b = \frac{u_0^2 a}{N u_y^2 C}, \; N = 5 \div 7,$$

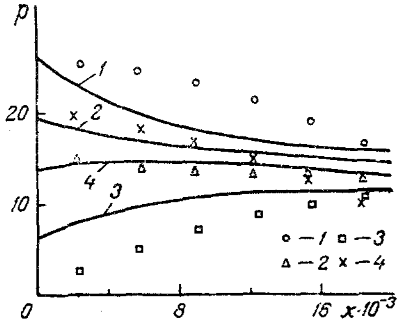

Fig. 2. Calculated (lines) and experimental [5] (points) data on the change in static pressure in sections of a plane jet: 1) y = 35 mm; 2) 25; 3) 10; 4) 50. p, kg/m²; $x \cdot 10^{-3}$, m.

for a plane jet

$$b = \frac{u_0 a}{1{,}6 u_y C},$$

where $C = 0.81 Ar^{-0.11} Re^{0.32}$.

Having solved problem (4) with these conditions, we obtain the distribution of the gradient of the filtration velocity potential φ and the value of the complex α/K by using an assigned value of the flow rate Q_0. The value of Q should be equal to the integral of the vertical component of filtration velocity over the top boundary of the bed. For a plane jet we take the expression

$$\frac{\alpha}{K} = \frac{L}{Q_0} \int_{-R}^{R} \frac{\partial \varphi}{\partial y}\, dx,$$

for an axisymmetric jet

$$\frac{\alpha}{K} = \frac{\pi}{Q_0} \int_{-R}^{R} \frac{\partial \varphi}{\partial y}\, x dx.$$

Having multiplied the resulting values of potential φ and its derivatives by the resulting value of the complex α/K, we obtain the actual pressure and gas velocities in the bed.

Figure 2 shows experimental data on the change in static pressure in sections of a plane jet of height 0.035 m in a granular bed of particles of polystyrene (d_e = 0.000274 m, nozzle 0.1 × 0.0018 m, H = 0.095 m). This data is from [5]. The figure also shows graphs of the change in static pressure calculated with the above model. It can be seen from the figure that there is satisfactory agreement between the theoretical and empirical data, especially with an increase in distance from the jet axis. The increase in the discrepancy between the theoretical and experimental data in the region near the cavity is apparently connected with the fact that the actual change in pressure on the boundary of the cavity is not linear and the cavity has a shape which differs from the shape assumed in the model. However, even in this region the calculated curves correctly reflect the character of the pressure change. Pressure decreases with an increase in distance from the jet axis in the upper sections of the cavity and increases in the sections close to the base of the bed. This indicates the presence of flows directed toward the interior of the cavity. It should be noted that the model proposed in [4] does not reflect this important feature.

Table 1 shows results of calculations in dimensionless form. These calculations were performed by introducing a linear scale equal to the nozzle diameter d = 1 and adopting the complex α/K = 100. The dimensionless height of the bed and jet and the radius of the unit were respectively equal to H = 4, b = 2, and R = 4. The resulting pattern of gas distribution is evidence of the presence of closed stream lines around the cavity, i.e., that part of the gas flow leaving the top part of the cavity and entering the bed is directed not toward the top boundary of the bed but downward, toward the plane of the gas-distributing grate. It rejoins the jet near the grate. The volume of gas injected by the jet can be determined by calculating the integral of filtration velocity over the surface of the cavity to the height at which there is a change in the sign of the horizontal component of this velocity from

TABLE 1. Vertical (numerator) and Horizontal (denominator) Components of the Dimensionless Filtration Velocity in the Vicinity of an Axisymmetric Jet

y	x: 0,0	0,2	0,4	0,6	0,8	1,0	1,2	1,4	1,6	1,8	2,0	2,2
2,6	58/0	58/11	54/17	47/19	41/19	35/18	30/16	26/14	23/12	20/10	18/8	17/7
2,4	75/0	75/20	66/28	56/29	46/28	38/25	31/21	26/18	22/15	19/12	17/10	16/8
2,2	106/0	106/40	86/47	67/45	51/39	40/33	32/27	26/22	21/18	18/15	16/12	15/9
2,0	166/0	166/91	115/82	80/68	56/54	41/43	31/34	24/27	20/21	17/17	15/13	13/10
1,8	—	—	149/141	91/101	58/73	39/54	28/41	21/31	17/24	15/18	13/14	12/11
1,6	—	—	—	91/139	53/93	33/65	22/46	17/34	13/26	12/19	10/15	10/12
1,4	—	—	—	—	36/110	20/71	13/49	10/35	9/26	8/20	8/15	8/12
1,2	—	—	—	—	−11/99	−1/69	1/48	2/34	3/25	4/19	5/15	5/12
1,0	—	—	—	—	—	−13/67	−10/43	−5/31	−2/23	1/18	2/14	3/11
0,8	—	—	—	—	—	−47/44	−24/32	−13/24	−6/19	−2/15	0/12	2/10
0,6	—	—	—	—	—	−56/19	−31/17	−17/16	−8/14	−4/13	−1/11	1/9
0,4	—	—	—	—	—	−55/−7	−29/3	−16/8	−8/10	−4/10	−1/10	0/8
0,2	—	—	—	—	—	−42/−29	−20/−6	−10/3	−5/7	−2/9	−1/9	0/8
0,0	—	—	—	—	—	0/−29	0/−6	0/3	0/7	0/9	0/9	0/8

negative (injection) to positive (ejection). Numerical studies showed that this height depends slightly on the geometric parameters of problem (4) and ranges within 0.25-0.30 of the cavity height for both plane and axisymmetric jets.

The pattern of distribution of gas velocity in the bed obtained from the above-described model makes it possible to explain the character of particle motion near the cavity: the stream lines of the gas correspond roughly to the trajectories of the particles.

In the lower sections of the cavity, the horizontal component of filtration velocity is directed inside the cavity. It reaches its maximum value as the flow approaches the plane of the base of the bed and the boundary of the gas jet. Since a particle located on the boundary of the cavity is not bound as strongly to the bed as other particles and experiences pressure directed inside the jet from the direction of the filtering flow, it is separated from the wall of the cavity and falls into the jet. Its place is taken by another particle which is subsequently drawn into the jet for the same reason. In the vicinity of the middle of the cavity, the horizontal component of filtration velocity is positive and is large enough to prevent particles from falling inside the cavity. The vertical component is either positive or negative but is small in magnitude and thus neither impedes nor facilitates the downward motion of particles under the influence of gravity to take the place of particles drawn into the jet. Near the top part of the cavity, the verticle component of filtration velocity reaches its maximum value. If we assume that the bed is fluidized near the top of the cavity, then the primarily radial motion of the particles can be explained by the sizable horizontal component of filtration velocity. Meanwhile, the maximum radial velocity of the particles will be seen not on the jet axis — where the horizontal velocity of the gas is zero — but at a certain distance from the axis, where the horizontal component of filtration velocity is also maximal.

Such an explanation of the circulatory character of particle motion in the vicinity of the cavity is qualitative in nature. A quantitative description of particle motion using the proposed model of gas distribution could be made by allowing for the rheological properties of the particles (see [7], for example).

NOTATION

a, b, initial radius and height of jet; H, R, height and width (radius) of unit; L, length of slot nozzle; p, static pressure; φ, potential of filtration velocity; U, u_0, u_y, gas veloicity, initial velocity of jet, and eddy velocity of particles; C, jet coefficient; α, drag coefficient; Q_0, gas flow rate; d_e, equivalent diameter of particles.

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RAREFACTION WAVES IN FREE CHARGES

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It was established experimentally that the form and velocity of a rarefaction wave in free charges depends on the particle size. Three regimes of wave propagation were observed — wave, with superposed filtration, and filtration through a stationary charge.

One of the important problems in chemical engineering is intensifying heat and mass transfer in heterogeneous catalytic processes.

Significant intensification is achieved with the application of pressure pulses to the gas flow. This creates rarefaction (RW) and compression waves in the bed of dispersed material. Such a regime is realized in the periodic injection of the initial gaseous reactants into the unit and the subsequent drop in pressure [1, 2].

To develop reliable methods of designing chemical reactors operating under nonsteady conditions, it is necessary to know the mechanisms of formation and velocities of these waves and the laws governing their decay in relation to the characteristics of the dispersed medium and gas.

The goal of the present study is to experimentally investigate the velocity and structure of RW's in free charges of different dispersed materials.

It is known [3] that the rate of propagation of disturbances in disperse systems ranges from several tens to hundreds of meters a second. Thus, the base length of the measurement chamber should be several meters. The passage of an RW may be accompanied by intensive motion of particles of the dispersed material, so it is desirable to observe the displacement of the top boundary of the material.

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