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WALL GAS-DYNAMIC INHOMOGENEITY IN A FIXED GRANULAR BED

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The porosity variation in a granular bed near a wall has been used to calculate the gas profile there for spherical and other surface shapes. Sectioning in a fixed bed affects the uniformity in the gas distribution.

When a granular material contacts a rigid wall bounding it or immersed in it, the random structure becomes ordered to a depth of 3-5 times the particle diameter [1], which increases the hydraulic radius r_h, i.e., increases the gas transmission cross section. For a spherical-particle bed, for which $r_h = \varepsilon d/6(1-\varepsilon)$, our data [1] on the local velocity distribution near a wall give the mean value $\bar{r}_h$ at 0.5d from the wall (Table 1) as 1.5 times that at the core.

The wall effect (increased speed) is related to $\epsilon = f(x/d)$, as has been confirmed by many measurements such as [2-4]. There are several ways of determining $w = f(\epsilon, r)$, analytically, as this is described by the differential equation

$$\frac{dP}{dz} = \mu_a \left(\frac{d^2w}{dr^2} + \frac{1}{r} \frac{dw}{dr} \right) - F(\varepsilon, w). \tag{1}$$

The [5] model gives the bed structure, in which the apparent viscosity μ_a for the infiltrating gas is considered as the same everywhere, apart from a thin layer near the wall (thickness ~0.35d), where $\epsilon = 1$. It has been supposed [6, 7] that the porosity near the wall varies exponentially:

$$\varepsilon = \varepsilon_0 [1 + C \exp(1 - 2x/d)], \tag{2}$$

where C in (2) was [6] fitted to suit ϵ_0, while in [7], C = f(d). In [8], $\epsilon = f(x/d)$ was approximated as a stepped function.

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TABLE 1. Mean Porosity $\bar{\epsilon}_d$ and Hydraulic Radius $\bar{r}_h$ at Distances x/d from a Wall

x/d	0,5	1	2	3	>5
$\bar{\varepsilon}_d$	0,5	0,48	0,44	0,41	0,4
$\bar{r}_h/d$	0,167	0,154	0,131	0,115	0,111
$\frac{\bar{r}_h}{d} \Big/ \left(\frac{\bar{r}_h}{d}\right)_0$	1,50	1,39	1,18	1,04	1,0

The actual variation in void fraction near the wall [9] is a damped cosine:

$$\varepsilon = \varepsilon_0 + \left(1 - \varepsilon_0 - \frac{\pi}{3,5}\left|\sin \pi \frac{x}{d}\right|\right) \exp\left(-\frac{x}{d}\right) \tag{3}$$

and

$$\varepsilon = \varepsilon_0 + \left(1 - \varepsilon_0 - \frac{\pi}{5}\left|\sin 0,8\,\pi \frac{x}{d}\right|\right) \exp\left(-2,3\,\frac{x}{d}\right) \tag{4}$$

correspondingly for spherical and arbitrary surface shapes.

(3) and (4) define the gas velocity distribution near the wall, which may be based on Brinkman's model [10], in that the physical viscosity μ is used in (1) instead of μ_a, which incorporates the velocity losses at the walls adjoining the bed but neglects losses at the particle surfaces. It has been assumed [11] that it is incorrect to specify attachment conditions at the walls bounding the bed as regards the average flow because such conditions are not imposed at the particle surfaces. We cannot accept this, but solving (1) while neglecting the viscosity term there gives an infinite wall velocity [11].

We consider a cylindrical apparatus filled with a granular bed and flushed by an isothermal flow of incompressible gas; the flow is stationary and axisymmetric. The resistance $F(\epsilon, w)$ in (1) exerted on the gas from unit volume is taken as linear in viscosity:

$$F(\varepsilon, w) = \frac{180\mu}{d^2}\left(\frac{1-\varepsilon}{\varepsilon}\right)^2 w, \tag{5}$$

where w is the gas speed with allowance for the particle hindrance. Here (5) applies strictly only for infiltration at low speeds and represents the first term most dependent on the void space in the more general nonlinear Ergan formula.

The right side in (1) is dependent only on r, and the left only on z, each of which should be equal to a constant, which we denote by $-a\rho$. Then

$$-a\rho = \mu\left(\frac{d^2w}{dr^2} + \frac{1}{r}\frac{dw}{dr}\right) - \frac{180\mu}{d^2}\left(\frac{1-\varepsilon}{\varepsilon}\right)^2 w. \tag{6}$$

Then (6) in dimensionless form is

$$\frac{d^2V}{dy^2} + \frac{1}{y}\frac{dV}{dy} - A\left(\frac{1-\varepsilon}{\varepsilon}\right)^2 V - A = 0, \tag{7}$$

in which

$$V = w\frac{b}{a};\quad b = \frac{180\mu}{d^2};\quad y = \frac{r}{R};\quad A = \frac{180R^2}{d^2}.$$

Boundary conditions:

$$V|_{y=1} = 0;\quad \left.\frac{dV}{dy}\right|_{y=0} = 0.$$

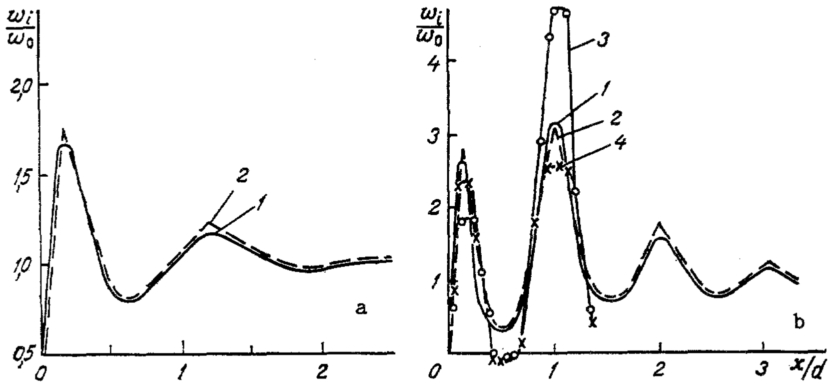

Fig. 1. Gas velocity distribution in a bed composed of particles with any shape (a) or spheres (b) near the wall: 1) computer calculation; 2) from (9) and (8) correspondingly for (a) and (b); 3 and 4) measurements [13] correspondingly for Re_d = 22 and Re_d = 500.

Figure 1 shows the computer solutions, which have been fitted to equations for the speed distributions near the wall in beds composed of spherical particles

$$\frac{w_i}{w_0} = \frac{x}{d} + \left(5 \sin 2{,}5\pi \frac{x}{d}\right) \exp\left(-5 \frac{x}{d}\right), \quad 0 \leqslant \frac{x}{d} \leqslant 0{,}5,$$
$$\frac{w_i}{w_0} = 1 + \left(5 - 2\pi \left|\sin \pi \frac{x}{d}\right|\right) \exp\left(-0{,}95 \frac{x}{d}\right) \quad \frac{x}{d} \geqslant 0{,}5 \tag{8}$$

and ones with any shape

$$\frac{w_i}{w_0} = 1{,}6 \frac{x}{d} + \left(4 \sin 2\pi \frac{x}{d}\right) \exp\left(-5 \frac{x}{d}\right), \quad 0 \leqslant \frac{x}{d} \leqslant 0{,}5,$$
$$\frac{w_i}{w_0} = 1 + \left(8{,}6 - 10 \left|\sin 0{,}8\pi \frac{x}{d}\right|\right) \exp\left(-3 \frac{x}{d}\right), \quad \frac{x}{d} \geqslant 0{,}5. \tag{9}$$

The velocity profile for spherical particles (Fig. 1b, curve 1) oscillates and is damped at (4-5)d from the wall. The maximum speed occurs at x/d = 1 and exceeds the mean speed at the core w_0 by more than a factor two. For an arbitrary particle shape (Fig. 1a), the maximum speed occurs directly by the wall (x = 0.17d), and w_i/w_0 = 1 for x/d > 2.

Wall gas velocity distributions have been obtained for beds of spherical particles from (8) and by laser anemometry [12, 13]; the two agree on the velocity variation near the wall. The differences in speed for x/d = 1 and small Re_d (Fig. 1b, curve 3) occur because the analytic solution does not incorporate the behavior in the space between particles, while in the experiments [12], the particle stacking was strictly cubic, whereas in our experiments [1] the particles were randomly packed in the wall layer in the voidage determination.

We used a moving thermoanemometer sensor having a tungsten filament 4 mm long in examining the air speed distribution in an immobile bed composed of glass particles (D = 150 mm). The thermoanemometer sensor was set at 5d above the bed and displaced gradually with a coordinate recorder from the wall towards the center, with the sensitive element always perpendicular to the motion.

The instantaneous local velocities w_φ and the pulsations were measured at intervals of 45°, i.e., along eight radii (velocities were measured at 176 points in the cross section). The signal passed to a digital voltmeter and was recorded for about 2 sec by an oscillograph.

The vertical component in the local velocity at any point is $\bar{w}_i = \frac{1}{8}\sum_{i=1}^{n} \bar{w}_\varphi$, and from the known $\bar{w}_i$ and w_φ we calculated the nonuniformity factor φ for the gas distribution [14]:

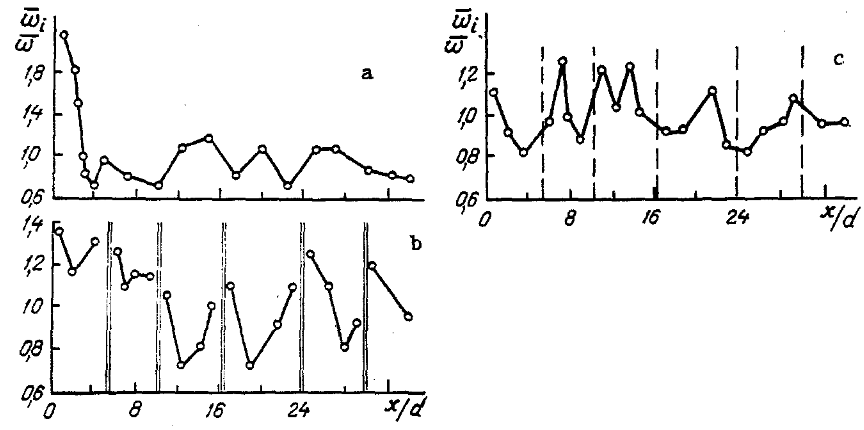

Fig. 2. Distribution for $\bar{w}/w_{\varphi}$ over the cross section of a granular bed unsectioned (a) or divided up by impermeable baffles (b) or perforated ones (c); d = 2mm, w_{φ} = 0.1 m/sec.

$$\varphi = \left[\left(\sum_{L=1}^{n} |\bar{w}_i - w_{\Phi}|\right) / n w_{\Phi}\right] \cdot 100\%.$$

We found that w_{φ} varied along the radius and also with the polar angle, i.e., the profile is not in general symmetrical (the same conclusion was drawn in [14]). Figure 2a shows a typical distribution for $\bar{w}_i$ averaged in time and with respect to angle and referred to w_{φ}. The $\bar{w}_i/w_{\varphi}$ pattern is a kinked line, whose general trend is that there is a marked increase in velocity near the wall, to distances of about 3d, which is also derived from the analytic solution (Fig. 1), with reduction towards the center.

There appear to be two basic reasons for this $\bar{w}_i = f(x/d)$ distribution: firstly, the speed increase at the wall is due to the increased hydraulic radius (Table 1). Secondly, the state of stress in the bed varies over the cross section [15], and the pressure exerted by the bed on the distributing grid is less near the wall, since the friction supports the granular material there. The particles are freer near the core and tend to sink under gravity and thus reduce the free cross section, the effect being greater than near the wall, with increased pressure on the distribution grid, which increases the hydraulic resistance at the center. Gas passing upwards ($w_{\varphi} < w_{cr}$) thus produces a form of valve effect, which has been described [16] for gas passing down through a fixed bed for $w_{\varphi} > w_{cr}$. The effects will increase with the diameter and bed mass.

It has been suggested that the effects from the wall on the distribution can be reduced by thickening the bed near the surface [17] or by introducing smaller grains there [18] or coating the walls with deformable material [11, 14]. All of these reduce the wall peak somewhat, but the inhomogeneity is not eliminated.

This inhomogeneity has considerable effects on the internal and external heat and mass transfer; these inhomogeneities arise from the structure and permeability in the bed and are dependent on the mode of loading, the particle shape, D/d, and many other factors, so it is virtually impossible to eliminate them. The main point therefore is to reduce the large-scale velocity fluctuations and produce a more uniform gas distribution.

One way of reducing the nonuniformity is to divide the bed up into several parts with vertical baffles.

Figure 2b shows the measured $\bar{w}_i/w_{\varphi}$ distribution for a bed split up with five concentric baffles having rigid walls and set at approximately equal distances apart. In each section, there is an uneven velocity profile. The scale of the fluctuations in $\bar{w}_{imax}/\bar{w}_{imin}$ is 1.23; 1.14; 1.50; 1.60; 1.56; 1.33, correspondingly for each of the six cross sections. Here φ = 20%, as against 40% for an unsectioned bed, and this reduction is due to the equalized resistances with the baffles, with more uniform distributions for the tangential and normal stresses. Nevertheless, the gas speed rises at the impermeable surfaces, so it is preferable to split up the bed by surfaces having perforated or permeable walls.

Figure 2c shows the relative speed distribution for a bed split up into six parts by concentric gridded baffles. The speed at the wall is reduced, and there are none of the characteristic peaks in $\bar{w}_i/w_{\varphi}$ found with impermeable baffles. The nonuniformity is reduced to 11%, i.e., by about a factor four less than for an unsectioned bed because the sectioning with perforated baffles favors resistance equalization, as with unperforated ones, while the perforated ones in a grid form do not produce the ordered bed structure characteristic of continuous walls, so there is no related gas break-through. The gas penetration into the wall zone is very much reduced, since there is no sharp change in resistance between that zone and the rest of the bed. The perforated baffles take up the radial gas flows and alter their directions to vertical, while the permeabilities cause these flows to disperse over the cross section, which reduces the large-scale inhomogeneity considerably, which affects the performance.

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