HYDRAULIC RESISTANCE OF A FIXED GRANULAR LAYER WITH RESPECT TO DESCENDING DUST-CONTAINING GAS FLOW

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The hydraulic resistance of a fixed layer with respect to a dust-containing gas flow is investigated experimentally. A correlation for calculating the resistance is obtained.

The flow of gas suspensions of dust, primarily in pipes or annular channels, has been investigated in a considerable number of publications, for instance, [1-4]. However, the use of through-flows of gas suspensions of dust in apparatus with a fixed granular packing bed offers promise for the realization of a number of chemical technology processes [2, 5]. Nevertheless, as far as we know, the laws governing through-flows containing solid particles for apparatus of this type have not been discussed in the literature. This prompted us to undertake this investigation, the results of which are given below.

We investigated granular layers consisting of smooth steel balls of roughly the same diameter and layers of round porcelain granules with a slightly rough surface. By immersing the grains in a measuring vessel containing water, we determined the mean volume V and the mean diameter d of the grains. Moreover, the mean surface area A of a grain was calculated for each type of layer. For balls, the value of A was defined as the surface area of a sphere with the mean diameter d. In the case of porcelain granules, we first measured the dimensions of grains in a typical batch along their principal axes. The surface area of a single grain was defined as the area of the mean ellipsoid.

Air is used as the gaseous component of the flow. Sand in three narrow size ranges and synthetic corundum 12 [GOST (All-Union State Standard) 3647-71] are used as the dispersed component. The geometric-mean dimension of mesh of the adjacent screens comprising the particle size range in question is used as the equivalent particle diameter. The equivalent diameter of synthetic corundum particles is calculated as the weighted-mean diameter in the narrow size range. The basic characteristics of the fixed granular layer and the dispersed component in the flow are given in Table 1.

The experiments are performed in an open device, which makes measurements of the mass discharges of the dispersed material and air simple and reliable. The disordered layer of granular material is placed in a column with a square cross section. One wall of the column is made of a clear plastic to permit visual observation of the motion of the dispersed material in the layer. In the first series of experiments (see Table 1), a column with a 150 × 150-mm cross section was used, while a column with an 80 × 80 mm cross section and a height of 600 mm was used in the other series. Air from a compressor at pressures of up to 0.6 atm (gage) at a temperature from 10 to 40°C reaches the upper part of the column after passing through a measuring diaphragm. The dispersed material also arrives there by gravity feed from the feed bin, which is located above the column. The dust-containing gas flow formed in this manner passes downward through the column with the granular layer, after which it is separated into individual components: The dispersed material settles in a dust-collecting bin, located under the column, while the dust-free air is released into the atmosphere.

The dispersed material discharge is regulated by means of a gate located under the feed bin, while the material dishcarge during an experiment is determined by weighing the particles settled in the dust-collecting bin with an error of not more than 0.5%.

The air discharge is calculated with respect to the pressure drop across the measuring diaphragm with an allowance for the flow density and temperature. The maximum possible error in determining the air discharge does not exceed 1.5%.

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TABLE 1. Basic Characteristics of the Fixed Granular Layer and the Dispersed Flow Component

Experimental series No.	Fixed layer of granular material		Dispersed component of the flow
	mater. and grain diam. d, mm	layer poros. in work. secs. ε	mater. and part. diam. d_p, mm
1	Steel balls, d = 25.4	0.421; 0.421	—
2	Steel balls, d = 15.3	0.440; 0.460	Synthetic corundum, d_p = 0.125
3	"	"	Sand, d_p = 0.15
4	"	"	Sand, d_p = 0.25
5	"	"	Sand, d_p = 0.70
6	Steel balls, d = 11.4	0.429; 0.410	Sand, d_p = 0.15
7	Porcelain granules, d = 6.26	0.382; 0.392	"
8	"	0.404; 0.406	Synthetic corundum d_p = 0.125

The branch pipes for static pressure readings divide the granular packing layer into four sections along the height of the column; the heights of the sections in the direction of the flow are equal to 200, 120, 120, and 60 mm, respectively. The first section serves for equalizing the flow over the transverse cross section of the layer ahead of the "operating" sections — the second and the third — where the pressure drop is measured. The layer porosity in the "operating" sections ε is calculated with an error of less than 1.0% on the basis of measurements of the volume of water poured to fill the intragranular space of these sections.

The following dependence is used for generalizing the experimental data on the resistance of the fixed layer to a descending dust-containing gas flow:

$$\frac{\Delta P_p - \Delta P}{\Delta P} = hk^{(1+n_1 k)}\,\mathrm{Re}^{n_2}\mathrm{Re}_t^{n_3}\left(\frac{d_l}{d_p}\right)^{n_4}\left(\frac{\rho_p}{\rho}\right)^{n_5}. \tag{1}$$

The parameters figuring in (1) and the type of the correlation function have been determined on the basis of dimensional theory and preliminary analysis of experimental data. The value of Re_t is determined by means of the interpolation formula given in [8]. The coefficients h, n_1, n_2, n_3, n_4, and n_5 are calculated by means of a computer, using the method of least squares. The following values have been obtained as a result of processing data from more than 600 experiments: $h = 0.287$; $n_1 = 0.00175$; $n_2 = 0.19$; $n_3 = -0.23$; $n_4 = -0.27$; $n_5 = -0.065$. The root-mean-square deviation of the experimental points (some of them are shown in Fig. 1) based on expression (1) is equal to approximately 10%. The correlation holds for the following intervals of variables: $1.75 < k < 143$; $140 < \mathrm{Re} < 11{,}000$; $9.8 < d_l/d_p < 59.5$; $9.5 < \mathrm{Re}_t < 270$; $1500 < \rho_p/\rho < 3300$.

It is readily seen that the absolute values of the exponents n_2, n_3, and n_4 are approximately equal to each other in the obtained correlation. Considering this and also neglecting the simplex ρ_p/ρ (because the exponent n_5 is a small quantity), we can generalize the results of experiments on the layer resistance to a dust-containing gas flow and represent them in simpler form:

$$\frac{\Delta P_p - \Delta P}{\Delta P} = Nk^{(1+n_1 k)}\left(\frac{\mathrm{Re}}{\mathrm{Re}_t}\cdot\frac{d_p}{d_l}\right)^m = Nk^{(1+n_1 k)}\left(\frac{u_l}{u_t}\right)^m. \tag{2}$$

The following values were obtained by processing the experimental data in this form: $N = 0.116$; $m = 0.21$. The root-mean-square deviation of the experimental points based on (2) was equal to 16%.

As follows from the above expressions, the parameter k exerts a strong influence on the rate at which the relative pressure loss in the layer increases. The dependence of the exponent of k on the value of k itself is clearly illustrated in Fig. 1. The role of the other parameters figuring in (1) and combined in the simplex u_l/u_t in expression (2) is less significant. For a fixed value of u_t, the additional pressure loss in the layer $(\Delta P_p - \Delta P)$ increases with the gas velocity.

In order to calculate the layer resistance to a dust-containing gas flow ΔP_p by means of expression (1) or (2), it is necessary to know the layer resistance to a pure gas flow ΔP.

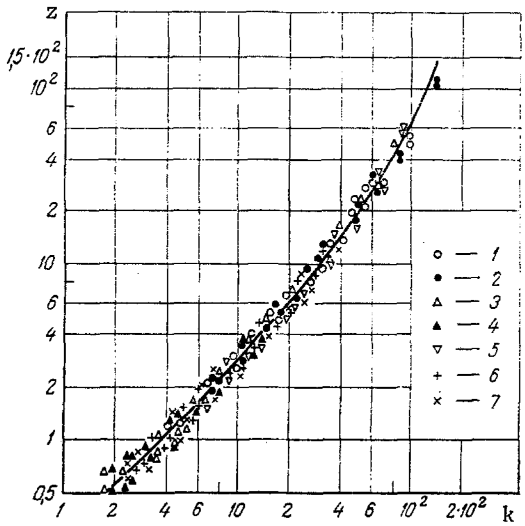

Fig. 1. Generalization of experimental data on the hydraulic resistance of a fixed granular layer with respect to a dust-containing gas flow:

$$z = \frac{\left(\dfrac{\Delta P_p - \Delta P}{\Delta P}\right)}{\mathrm{Re}^{0,19}\mathrm{Re}_t^{-0,23}\left(\dfrac{d_l}{d_p}\right)^{-0,27}\left(\dfrac{\rho_p}{\rho}\right)^{-0,065}};$$

k is the discharge concentration of the dispersed material (kg/h/kg/h); 1-7) experimental data from series Nos. 2-8, respectively (see Table 1).

For this purpose, we have investigated the dependence of ΔP on the granular packing geometry and the conditions of gas flow. For each series indicated in Table 1, the experiments on the determination of ΔP were performed twice: before and after the flow had passed through the layer. This is connected with the fact that the geometry of the granular packing and, consequently, the value of ΔP can change considerably in such systems in connection with the "contamination" of the layer by particles of the dispersed material. We do not contemplate here large particles, commensurable with the size of pores in the layer, which can become clogged by such particles; their use in devices of this type would make no sense. We consider relatively small particles, which can readily pass through the layer; however, experiments show that some of these particles can become stuck at the places of contact between the grains of the layer, while the smallest particles can adhere in the form of a thin layer to the surface of grains and the apparatus walls.

The experimental data on the layer resistance to a pure gas flow are processed in the form of a ξ versus Re plot. The value of ξ for each experiment is calculated by means of the expression corresponding to the capillary model of the granular layer [6]:

$$\Delta P = \xi \frac{u^2\rho}{2\varepsilon}\, [a(1-\varepsilon) + 0.75\, a_w]\, l. \tag{3}$$

The Reynolds number characterizing the gas flow conditions is defined as follows:

$$\mathrm{Re} = \frac{u_l d_l \rho}{\mu} = \frac{4u}{[a(1-\varepsilon) + 0.75\, a_w]} \cdot \frac{\rho}{\mu}. \tag{4}$$

In correspondence with the capillary model, a change in the geometry of the granular layer caused by its "contamination" by particles of the dispersed material should manifest itself in a reduction in the porosity ε and an increase in the values of the specific surface areas a and a_w figuring in (4) and (5). However, in data processing, the results of which are given in Fig. 2, it was considered conventionally that the initial layer parameters ε, a, and a_w remained unchanged after the flow passed through the layer, while the degree of layer "contamination" was accounted for directly by the quantity ξ. This is connected with the fact

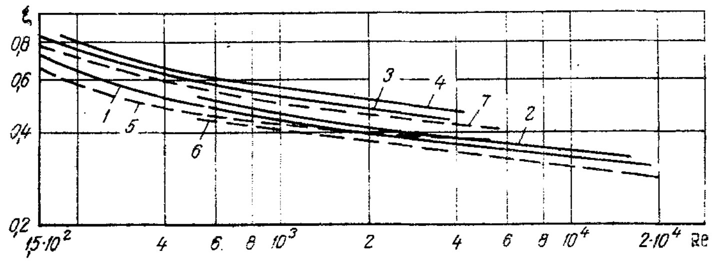

Fig. 2. Hydraulic resistance coefficient of a fixed granular layer with respect to a pure gas flow ξ as a function of Re. Before passage of the dust-containing gas flow through the layer: 1) series Nos. 1-8 (140 < Re < 18,000); 5) 1 < Re < 5000) [7]; 6) (500 < Re < 50,000) Denton's data, processed in [6]; 7) (45 < Re < 5500) [9]. After passage of the dust-containing gas flow through the layer: 1) series Nos. 3-6; 2) No. 2; 3) No. 7; 4) No. 8.

that direct measurement of the values of a and a_w that have changed as a result of layer "contamination" is extremely difficult.

Curve 1 in Fig. 2 describes the dependence of ξ on Re for all investigated types of granular packing (see Table 1) in experiments performed before the passage of the dust-containing gas flow through the layer; it is defined by the expression

$$\xi = \frac{37}{\mathrm{Re}} + \frac{0.712}{\mathrm{Re}^{0.085}}. \tag{5}$$

This expression has been derived for the following ranges of the variables: $140 < \mathrm{Re} < 18{,}000$ and $0.382 < \varepsilon < 0.46$. The root-mean-square deviation of the experimental points based on (5) is equal to approximately 6%. For comparison, this figure also provides curves 5, 6, and 7, which have been plotted on the basis of correlations provided by other authors. These correlations approximate experimental data on the resistance of "uncontaminated" ball packings for limited ranges of the Re number. Considering that curves 5, 6, and 7 are in satisfactory agreement with expression (5), we can recommend the latter as a generalized correlation suitable in the range of Re numbers from 1 to 50,000.

Processing of the results of experiments performed after passage of the dust-containing gas flow through the layer has shown that the resistance coefficient ξ in series 3-6 remains unchanged [expression (5)], while it increases (curves 2-4) in series 2, 7, and 8 in connection with layer "contamination" by particles of the dispersed material. It was observed that layer "contamination" by particles in series 2, 7, and 8 occurred during a short interval of time and up to a certain degree. Subsequently, the degree of layer "contamination" was independent of the duration of dispersed material feed, and it varied slightly with changes in the flow velocity (curves 2-4 are almost equidistant with respect to curve 1). Considering the latter, we can represent the dependence of ξ on Re for the general case by means of the expression

$$\xi = \Psi\left(\frac{37}{\mathrm{Re}} + \frac{0.712}{\mathrm{Re}^{0.085}}\right), \tag{6}$$

where Ψ is a coefficient which accounts for the degree of layer "contamination." For "uncontaminated" layers, Ψ = 1, while, for "contaminated" layers, Ψ > 1.

Under our experimental conditions, the value of Ψ depends mainly on the state of the surface and the dimensions of grains in the layer as well as the dimensions and shape of the dispersed component particles in the flow. Thus, "contamination" of a layer of steel balls with a smooth surface is observed only in experiments with synthetic corundum (series 2), whose particles are characterized by an irregular shape. Moreover, the composition of synthetic corundum comprised fine particles (approximately 20 μm). In this series of experiments, the coefficient Ψ was equal to 1.05 (curve 2 in Fig. 2). In experiments on a layer of porcelain granules (series 7 and 8) with a rough surface and a diameter smaller than that of the steel balls, the degree of layer "contamination" increased: During the passage of round sand particles with d_p = 0.15 mm through the layer, we found Ψ = 1.18, while, in the case of synthetic corundum particles with d_p = 0.125 mm, Ψ = 1.27 (curves 3 and 4 of Fig. 2, respectively).

It follows from the above that expression (1) or (2) with an allowance for (3)-(6) generalizes satisfactorily the results of experiments on the resistance of a granular layer to a descending dust-containing gas flow. The accuracy in calculating the layer resistance depends on the reliability of the Ψ value used. If such data are not available, one could use the values of Ψ obtained in our experiments.

NOTATION

$a = A/V$, specific surface area of grains in the layer; $a_w = 4/D$, specific surface area of the column walls; D, dimension of the column side; d, diameter of sphere whose volume is equal to the grain volume in the layer; d_p, diameter of dispersed component particles in the flow; $d_l = 4\varepsilon/[a(1-\varepsilon) + 0.75a_w]$, equivalent diameter of the pore channel in the fixed layer; l, layer height; ΔP, ΔP_p, hydraulic resistances of the fixed layer with respect to gas flow and flow of a gas suspension of dust, respectively; k, discharge concentration of the dispersed component in the flow; $Re \equiv u_l d_l \rho/\mu$, Reynolds number for a pore channel in the layer; $Re_t \equiv u_t d_p \rho/\mu$, Reynolds number based on the terminal velocity of particles; u, gas velocity through the unfilled column section; u_t, terminal velocity of particles; $u_l = u/\varepsilon$, gas velocity in the intergranular space in the layer; ε, porosity of the fixed layer; ξ, coefficient of the hydraulic resistance of the fixed layer to gas flow; μ, dynamic gas viscosity; ρ, ρ_p, gas density and density of the dispersed component particles in the flow; Ψ, coefficient accounting for the degree of layer "contamination."

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